Numerical Weather Prediction

Parallel trials of enhanced vertical and horizontal resolution in the global Unified Model

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1 Introduction

Following the procurement of the CRAY T3E at UKMO the plan is to increase the resolution of the NWP versions of the global and mesoscale Unified Model (UM). Comparison with other operational NWP centres shows that the UKMO global model has a coarser resolution than other models in both the vertical and horizontal.

This report discusses the results of parallel trials to test an enhanced resolution version of the global UM. Section 2 outlines the changes to model vertical and horizontal resolution and gives details of the parallel trials. Section 3 considers the impact of resolution on the known systematic errors in the global UM. Objective verification of the forecasts against both analyses and observations (e.g radiosondes, SYNOPS's) is discussed in section 4 and a subjective assessment of individual forecasts discussed in section 5. A summary of the impacts is given in section 6.

2 Model configuration and details

2.1 Resolution Changes

The vertical and horizontal resolution have both been enhanced in the global UM. The vertical levels have been increased from the 19 hybrid levels to 30 hybrid levels (Fig. 1). Most of the extra levels are in the free troposphere and concentrated near the tropopause. Vertical resolution in the boundary layer is kept similar at the two resolutions, following earlier studies (Wilson and Hammon, 1995a; Wilson and Hammon 1995b) which showed that increasing the levels in the boundary layer lead to excessive low level cloud and increased the model's cold bias. Proposed developments to the boundary layer parametrization in the UM may address this issue in the near future. The changes to horizontal resolution are from 217 x 288 latitude/longitude points to 325 x 432 latitude/longitude points. This is an increase of resolution from 90km to 60km (in mid-latitudes), which makes the enhanced horizontal resolution in the global UM similar to the resolution of the current Limited Area Model (LAM). The model is currently run with a 15 minute physics timestep with 3 sweeps of the dynamics. Attempts to use a longer timestep of 20 minutes have lead to one case of numerical instability and this is under investigation.

The assimilation cycle included the 1D Variational Assimilation of TOVS radiances (GLOSS, Gadd et. al.,1995). The model background (6hr) humidities (q) and temperatures (T) are converted to radiances using a radiative transfer model and combined with the TOVS radiances to give 'optimal' temperature and humidity profiles for use in the assimilation. For the CONTROL the model background T and q are interpolated from the 19 model levels to 18 pressure levels and then to 40 pressure levels used in the radiative transfer model. The HIRES temperatures and humidities go from 30 model levels to 30 intermediate pressure levels and then to the 40 radiative transfer levels. For the HIRES one weeks worth of forecasts were run in both January and July in order to retune the GLOSS bias corrections (see Eyre(1992) for details of the bias correction). These new bias estimates were then used in the 3 week trials. Finally we note that no tuning of parametrizations was carried out. The only parameters that were changed were the horizontal diffusion coefficients which were changed from the global values of $4.00\text{x}10^{7}\nabla^{4}$ ($1.00\text{x}10^{6}\nabla^{2}$ in top model level for u,v, and T) to those used in the LAM, $2.00\text{x}10^{7}\nabla^{4}$ ($7.00\text{x}10^{5}\nabla^{2}$ in top model level for u,v, and T). The divergence damping coefficients in the assimilation were also changed from $1.00\text{x}10^{6}\text{m}^{2}\text{s}^{-}1$ to $5.00\text{x}10^{5}\text{m}^{2}\text{s}^{-}1$

2.2 Details of the parallel trials

Parallel trials were run for January and July 1997. For the January trial the UM assimilation cycle was run for both operational resolution (CONTROL) and enhanced resolution (HIRES) for a 27 day period covering 00UTC 02/01/97 to 12UTC 28/01/97. A total of 21 six day forecasts were run from 12UTC analyses between 02/01/97 and 22/01/97 for both CONTROL and HIRES. The July trial covered the period 00UTC 02/07/97 to 12UTC 28/07/97. We concentrate on the January results except in cases where the impacts were different for January and July.

It should be noted that two errors were found in the HIRES runs which affected the Southern Hemisphere (SH) results. Firstly the land sea mask used had not been quality controlled and as a consequence the Ross and Ronne ice shelves in Antarctica which are normally defined as ice covered land were actually defined as "sea ice" in the HIRES. This meant that the HIRES had an additional sensible heat flux over these regions. A further error was found in the data assimilation which affected the assimilation of surface pressure from the observation made at Amundsen-Scott South Pole station. This was a simple problem of an array containing increments being dimensioned too small for the enhanced resolution. In the influence area of an observation, where the points are filled from N to S, the effect was to generate a donut shaped increment field for an ob at the south pole (ie zero increments near the ob and correct increments further from the ob). The largest impact from this error appears to have been in the July trial, for reasons not fully understood. A week of the July cases have been rerun with these two errors corrected. This is discussed further in section 4.

3 Impacts on model systematic errors

The impact of enhanced resolution on the day 3 and day 5 mean errors in the UM is discussed in this section. The HIRES mean errors are formed from the difference of HIRES forecasts from HIRES analyses, and similarly for the CONTROL mean errors. Details of the current systematic errors identified in the UM can be found in Milton and Wilson (1996).

3.1 Wind Fields

3.1.1 Zonally Averaged Fields

For January the impact of enhanced resolution is to reduce the westerly zonal wind polewards of the subtropical jets in both hemispheres (Fig. 2(c)). This leads to a reduction in the westerly bias in these locations in HIRES(Fig. 2(d)) compared to CONTROL(Fig. 2(b)). For example at 40°N and 250hPa the westerly wind bias is reduced from 2.5 ms^{-1} to 0.5 ms^{-1}. There is also a reduction in the westerly bias in the stratosphere (above 100hPa) in both hemispheres and in the zonal wind errors over the Antarctic. The impact of HIRES (Fig. 2(c)) on the zonal wind is very symmetric about the equator and reflects a consistent improvement in the general circulation with enhanced resolution (see discussion of momentum balance in section 3.1.3). In the tropics the tendency for the trade winds to be too intense in the tropical boundary layer is reduced in HIRES, as is the westerly bias in the mid and upper troposphere at 15°S. The only region where the mean errors are worse in HIRES is in the tropical upper troposphere at 100hPa over the equator where the easterly bias is larger.

In July (Fig. 3) the improvements are less marked but still apparent between 60°N and 50°S. However, over Antarctica we see an increase in the easterly bias over the continental interior and in the westerly bias over the edge of the continent. These errors can be attributed to the incorrect analysis of the South Pole observation, and recent reruns correcting this error do not show the same large errors. There are also large increases in the mean errors over the northern polar regions in HIRES which are under investigation.

The biases in the meridional wind for January 1997 are largely unchanged, and the global UM still suffers from too strong a Hadley circulation (Fig. 4(d)).

3.1.2 Extratropical 250hPa Winds

We now consider the geographical distribution of systematic errors in the jet level winds. In the Northern Hemisphere (NH) the mean errors in the CONTROL forecasts (Fig. 5(b)) show an increase in wind speed to the south of the Atlantic subtropical jet core and a decrease to the north. These errors stretch from the Rocky Mountains to Northern Europe and make a large contribution to the errors noted in the zonally averaged zonal wind. The forecast difference field (HIRES - CONTROL, Fig. 5(c)) shows that the greatest impact from enhanced resolution is over the U.S., Atlantic and Europe, and is in the sense to correct the errors seen in the CONTROL forecasts.Consequently, the errors are smaller in the HIRES forecasts (Fig. 5(d)). For example the +5 ms^{-1} and +10 ms^{-1} error contours cover a much smaller geographical area. There are also smaller improvements in HIRES forecasts of the Pacific subtropical jet near Japan.

The jets in the SH also show reductions in mean errors at day 5 (Fig. 6). The tendency to predict too strong wind speeds to the south of Australia in the CONTROL is improved in the HIRES.

3.1.3 Momentum Balance

Resolved Scale

The zonal momentum balance of the zonally averaged and time averaged flow can be expressed as (ignoring vertical advection)

$$\overline{\frac{\partial[u]}{\partial t}} = -f[\overline{v}] - \frac{\partial[\overline{u}][\overline{v}]}{\partial y} - \frac{\partial[\overline{u*v*}]}{\partial y} - \frac{\partial(\overline{[u'v']})}{\partial y} - [F_u] \qquad (1)$$

This is an expression of the balance between (i) divergence of the northward momentum flux by the mean meridional flow, stationary eddies and transient eddies and (ii) the last term, which represents all of the subgridscale frictional terms, parametrized in the UM as gravity wave drag, turbulent boundary layer mixing (including the effects of orographic roughness) and vertical diffusion (Tropics only). Figure 7 shows the zonally averaged profile of the total northward momentum flux ($\overline{[uv]} = [\overline{u}][\overline{v}] + [\overline{u*v*}] + \overline{[u'v']}$) at 200hPa for January 1997 . HIRES and CONTROL analyses both have similar flux profiles with maxima at 25°N and 35°S just equatorwards of the subtropical jet. The day 3 CONTROL forecasts show a large increase in the northward momentum flux at 25°N, consistent with the increase in the westerly bias in the zonal wind. The HIRES day 3 forecasts have a momentum flux profile which is much closer to analysed values, particularly at 25°N. These results suggest improvements in the transports of momentum on the resolved scale associated with the enhanced resolution.

Subgrid Scale

Vertical profiles of the zonally averaged zonal momentum balance for the extratropics (60°N-30°N) and Tropics (10°N-10°S) are shown in figure 8 and figure 9 respectively. In the extratropics the tendency of the dynamics to accelerate the westerly flow is balanced by the parametrized drag (Fig. 8(a)). There is evidence of a residual westerly tendency at 250hPa and in the boundary layer and a residual easterly tendency in the stratosphere, as shown by the total tendency term (parametrizations+dynamics). The changes in the zonal momentum balance due to increasing resolution are complex ((Fig. 8(b)). However, the net impact of changes in both parametrized and resolved terms is an easterly tendency of -0.05 $ms^{-1}day^{-1}$ throughout the atmosphere. This is in qualitative agreement with the reduction in the westerly bias noted for the zonal wind at these latitudes. The source of these changes are;

- *Reduction in the westerly momentum tendency from the dynamics in the upper troposphere* - the westerly tendency provided by the advection terms has been reduced (in agreement with the reduction in total northward momentum fluxes), with largest changes of -0.5 $ms^{-1}day^{-1}$ at 200hPa (Fig. 8(d)). These changes in advection are partially balanced by changes in the adjustment and in convective momentum transports.

- *increased parametrized drag in the lower troposphere* - due to increased drag from the boundary layer scheme, but also a 40% reduction in the westerly momentum source provided by the convective momentum transport parametrization. Overall the the role of convective momentum transports has been reduced in HIRES compared to CONTROL. This may reflect the response of the convection scheme to a new equilibrium state.

It is interesting to compare the changes in convective momentum and gravity wave drag (GWD) parametrizations. The GWD in the CONTROL forecasts is of order -1 $ms^{-1}day^{-1}$ in the boundary layer and stratosphere (Fig. 8(c)). The GWD is reduced in HIRES, but the changes are only of the order 10% and are smaller than changes in convective momentum transports (Fig. 8(d)). These arguments take no account of the role such small changes in parametrized GWD may actually have on the flow in a fully non-linear NWP model. The reduction in GWD with enhanced resolution may be anticipated as the surface stress in the GWD scheme is dependent on the standard deviation of orography in the gridbox. This will decrease in magnitude as the grid boxes become smaller.

The tropical momentum balance in the CONTROL forecasts (Fig. 9(a)) shows that the easterly accelerations from the dynamics in the boundary layer and upper troposphere are only partially balanced by the parametrized drag leading to a residual easterly tendency of -0.5 $ms^{-1}day^{-1}$ in the upper and lower troposphere. Again the change in the momentum balance (HIRES - CONTROL) is complex (Fig. 9(b)). The 200hPa residual easterly tendency is made worse, largely through a reduction in the parametrized drag. The major terms contributing to this change are the convective momentum transports and vertical diffusion. The convective momentum transports have been reduced in the HIRES forecasts (Fig. 9(d)). Changes in advection and adjustment approximately balance each other.

In summary, there is an improved momentum balance in the extratropics with enhanced resolution. This appears to be largely due to better modelling of the dynamical transports, probably through more accurate horizontal advection, and leads to a reduction in the westerly bias in the UM in the extratropics during January 1997. However, the tropical momentum imbalance at 200hPa is made worse and more work is required to understand this response.

3.2 Mean sea level pressure (MSLP)

The HIRES-CONTROL difference for NH MSLP at day 5 (Fig. 10(c)) reflects the decrease in the westerly bias noted for the zonal wind (Fig. 2). There is lower pressure between 30°N-60°N and higher pressure between 60°N-90°N in the central Pacific, Atlantic and over North America. On the whole this gives smaller mean errors in HIRES (Fig. 10(d)) compared to CONTROL (Fig. 10(b)), particularly over the Pacific, North America (Rockies) and U.K. and Europe. The negative bias in the western Atlantic is made worse.

In the SH (Fig. 11) the circumpolar trough is less deep and hence more accurate in the HIRES forecasts, and equatorwards of this we see a beneficial decrease in pressure (Fig. 11(c)). The mean errors in the Pacific Ocean, from Australia through to South America, are considerably smaller in HIRES (Fig. 11(d)). An example is the large reduction in the negative bias to the south of Australia. Many of the improvements to errors in the upper level wind fields can be linked to the improvements in the MSLP field. The errors to the south of Australia in MSLP and 250hPa wind speed are a good example.

For July the impact of enhanced resolution is to increase pressure over the land and decrease pressure over the oceans(Fig. 12(c)). On the whole this is beneficial in reducing the biases in the CONTROL forecasts (Fig. 12(b)), particularly around the Gulf of Alaska and over Newfoundland, although the high pressure bias over central Russia is worse. The low pressure error to the south of Japan in the HIRES forecasts is due to a single forecast of a deeper tropical cyclone in HIRES (see discussion of tropical cyclones in section 5).

3.3 Relative Humidity and Cloud

3.3.1 Zonal Average fields

Increasing the resolution leads to a reduction in the relative humidity in HIRES forecasts compared to CONTROL forecasts over most of the troposphere (Fig. 13(c)). The largest impact is in the upper troposphere. In the NH extratropics the moist bias of 16%-20% in the CONTROL (Fig. 13(b)) is reduced to 12% in HIRES (Fig. 13(d)). In the tropics the moist bias at 100hPa in the CONTROL is over 38%. This is reduced to just 12% in HIRES. One detrimental impact is the increased drying in the tropical mid-troposphere in the HIRES forecasts.

The response in the tropical upper troposphere to increased resolution is particularly interesting. Although the moist bias is reduced in HIRES (Fig. 13(d)) compared to CONTROL (Fig. 13(b)), the difference between the two day 5 forecasts (Fig. 13(c)) shows that HIRES is actually moister than CONTROL between 200-100 hPa. This bias is reduced because the HIRES analyses themselves are considerably moister than the CONTROL analyses, and in closer agreement with the upper tropospheric moisture in the HIRES forecasts. This effect can be seen in figure 14 which shows the tropical upper tropospheric specific humidity profiles. In the tropics at 100hPa the CONTROL forecasts are considerably moister than the CONTROL analyses. However, both the HIRES forecasts *and* HIRES analyses are moister than the CONTROL forecast/analysis. In addition, the HIRES forecasts show very little drift from the HIRES analyses, hence the smaller moist bias in the HIRES. The real issue is whether we believe the HIRES or CONTROL moisture analyses to be more accurate. Work is underway to try and validate the upper tropospheric humidities in the model against TOVS water vapour channels (see for example Chen et. al. (1996)). For the lower and mid troposphere the relative humidity biases measured against

radiosondes are clearly reduced in the HIRES compared to CONTROL in both the extratropics and tropics (Fig. 15)

The moisture profiles in the extratropics (50°N) show a different signal ((Fig. 14). The CONTROL and HIRES analyses are now in good agreement. The CONTROL forecasts show a moistening at 200hPa and drying at 100hPa relative to the CONTROL analyses. The 'drift' in the HIRES is smaller than the CONTROL at 200hPa, while at 100hPa there is no evidence of drying in the HIRES forecasts. Independent tests show that most of the reductions in the moist biases in HIRES can be attributed to the increased vertical resolution, and are probably the result of improved vertical advection of moisture due to the extra resolution near the tropopause.

Reductions in upper tropospheric humidity in HIRES also lead to reductions in layer cloud (Fig. 16) and convective cloud (Fig. 17) fractions. This has a bearing upon the temperature biases and thermal balance in the UM at tropopause level (see section 3.5.3). Both layer and convective cloud fractions are increased in the tropical boundary layer. This is thought to be beneficial as comparisons with the ISCCP cloud products and the Warren climatology suggest we have too little tropical/subtropical cloud (see Milton and Wilson, 1996).

3.3.2 Moisture Balance

Finally, we consider in more detail the upper tropospheric and stratospheric moisture balance (300hPa - 5hPa) in the extratropics (60°N-40°N). The dominant balance is between the dynamics and the convective parametrization (Fig. 18(a)). The total tendency for the CONTROL forecasts (Fig. 18(a)) shows the moistening of the layers between 300hPa and 150hPa. Below 200hPa this moistening is due to the convection scheme detraining at these levels. Above 200hPa it is the dynamics which makes the largest contribution to the moistening tendency. At 100hPa the drying tendency is entirely due to the dynamics.
Figure (18(b)) shows the changes in the moisture balance (HIRES - CONTROL). The change in total tendency shows that the HIRES forecasts have reduced both the excessive moistening (300-150 hPa) and drying (100hPa) seen in the CONTROL moisture balance. The reduction in the moistening tendency can be attributed to

- Reduced *convective moistening* at 250hPa.
- Reduced moistening due to the *dynamics* from 200hPa to 150hPa.

The drying tendency at 100hPa has also been reduced due to changes in the dynamical transports in the HIRES forecasts. Given that the tropical humidity distributions in the CONTROL and HIRES analyses are so different we have not considered the tropical moisture balance in any detail.

3.4 Precipitation

The only significant changes to the precipitation in January 1997 is in the NH extratropics. The large scale precipitation shows an increase of around 10% (Fig 19(a) and (b)) which is consistent with increases in latent heating noted in the thermal balance (see section 3.5.3). Most of this increase occurs in the NH stormtracks. Comparisons with the GPCP (Global Precipitation Climatology Project;Huffman, et.al., 1996) precipitation estimates suggest that

the current UM has too little precipitation in the stormtrack regions, so the increases in HIRES may be beneficial. Previous studies of the thermal budget (Milton, 1993) have also suggested a lack of diabatic heating in the stormtracks in the current operational model. The NH large scale precipitation also shows a spinup with forecast range which does not improve with enhanced resolution. Convective precipitation is virtually unchanged (Fig 19(c) and (d)).

3.5 Temperature

3.5.1 Zonally Average Fields

Temperatures are warmer at the extratropical tropopause in the HIRES forecasts by up to 0.8 K (Fig. 20(c)). This reduces the persistent cold bias in this region. We also see a warming throughout the troposphere of both hemispheres at 30N-60N and 60S-80S which is again beneficial. The Tropics are colder in HIRES relative to CONTROL (Fig. 20(c)), which reduces the tropical mid-troposphere warm bias, but enhances the cold bias in the tropical upper troposphere. These changes are discussed in more detail in section 3.5.3 where the thermal balance in HIRES and CONTROL is examined.

3.5.2 Temperatures at 850 hPa

The largest impacts on 850hPa temperature in January 1997 are over North America (Fig. 21). The mean error in the CONTROL forecasts shows a warming of over 5K in NW Canada and a cooling of up to -3K over the continental U.S. The impact of HIRES is to warm over the continental U.S and cool over NW Canada, reducing the mean error seen in CONTROL. The HIRES forecasts are also 1K to 2K warmer in the mid Atlantic and mid Pacific Oceans. This warming can also be seen at 500hPa and is associated with increased precipitation in the stormtracks and increased diabatic heating (see section 3.5.3).

3.5.3 Thermal Balance

In order to investigate the source of the improvements in the extratropical temperature fields we have examined the thermal balance of both HIRES and CONTROL forecasts.

Figure 22(a) shows the 24 hour total tendency (dynamics + parametrizations) in zonally averaged temperature from the CONTROL forecasts. Over a large enough sample of cases this tendency should be close to zero if the model is in thermal equilibrium. The total tendency bears a strong resemblance to the systematic errors in temperature in the UM. We have a cooling at the tropopause of 0.4 K/day, a cooling in the SH lower troposphere, and a warming at the tropical mid troposphere. The difference in total tendency between HIRES and CONTROL (Fig. 22(b)) is in the opposite sense to the CONTROL total tendency (Fig. 22(a)). This shows that the HIRES is closer to thermal equilibrium than the CONTROL. The tropopause cooling tendency is reduced in HIRES, as is the warming tendency in the tropical mid-troposphere. This in agreement with reduced mean errors in temperature in the HIRES forecasts discussed earlier(see Fig. 20).

Figure 23(a) shows vertical profiles of the thermal balance in the CONTROL forecasts between 60°N-30°N. The total tendency shows cooling in the boundary layer (1000hPa-850hPa), upper troposphere (500hPa-150hPa), and stratosphere of order -0.4 $Kday^{-1}$. In the upper troposphere the cooling tendency arises because the parametrized cooling is larger than the warming from the

dynamics. The differences (HIRES-CONTROL) in thermal balance (Fig. 23(b)) show the total tendency in the HIRES is warmer in the upper troposphere and in the boundary layer, reducing the erroneous cooling tendency seen in the CONTROL forecasts. In the upper troposphere contributions to this warming come from a reduced cooling due to the parametrizations and an increase in the warming from the dynamics. The individual parametrized terms (Fig. 23(c) and (d)) show the decrease in upper tropospheric cooling is largely due to reduced Longwave (LW) cooling, consistent with the reductions in upper tropospheric layer cloud (Note: the changes in the cloudy component rather than clear sky dominate the total change in LW). In the lower troposphere there is an increase in the turbulent mixing from the boundary layer parametrization which contributes to the reduced cooling tendency in HIRES. In the mid troposphere we see an increase in the latent heating from the formation of large scale cloud. This is consistent with increased vertical motion and increased dynamical precipitation in the stormtrack regions and is beneficial.

In the Tropics (10°N-10°S) the HIRES forecasts show an increase in the cooling tendency in the upper troposphere (Fig. 24), consistent with the increased cold bias noted earlier. This cooling tendency comes from decreases in the parametrized heating at 300hPa (Fig. 24(b)). The changes are again dominated by changes in the radiative heating (Fig 24(d)). From 300-100 hPa both the layer and convective cloud is reduced in HIRES (see Fig. 16 and Fig. 17 respectively). This leads to reductions in both the SW heating and LW cooling near cloud top. These two changes in SW and LW approximately balance each other at 250hPa-100hPa (Fig. 24(d)). However, at 300hPa there is an increase in the LW cooling tendency of -0.4 Kday^{-1}. This may be explained by the fact that the LW radiative impact of high tropical cloud is to warm the atmosphere locally in the vicinity of the cloud base (see Slingo and Slingo, 1988). The decrease in layer cloud implies a decrease in LW *cloud forcing* (i.e a reduced warming tendency) at cloud base.

There are large uncertainties as to what are realistic cloud fractions at the tropopause and also what the cloud radiative properties of these clouds are. The best we can say from this study is that cloud has been reduced in the HIRES model which has an impact on the temperature field through changes in cloud radiative forcing which appear to beneficial in the extratropics and detrimental in the tropics.

3.6 Extratropical Variability

3.6.1 Variance of 500hPa Geopotential Height

Given the increase in resolution we might expect the variability of both forecasts and analyses to increase. Figure 25 shows the variance of the NH 500hPa geopotential height field for CONTROL and HIRES forecasts and analyses. The variance is calculated in time across the sample of 21 forecasts and analyses. The variance is increased in the HIRES analyses compared to CONTROL (Fig. 25(c)). The HIRES forecasts show even larger increases in variance of between 10% - 20%. This increased variance has implications for the verification of forecasts using Root Mean Square Errors (RMSE). The mean square error (MSE) of forecast (f) versus analysis or observations (assigned subscript v) can be decomposed into the following terms

$$MSE = b^2 + s_f^2 + s_v^2 - 2 s_f s_v r \tag{2}$$

The MSE (and RMSE) are therefore sensitive to the size of the bias (b^2), forecast and analysis/observation variance (s_f^2 and s_v^2) and the correlation (r) between forecast and analysis (or

observations). Changes in any one of these can lead to changes in the MSE or RMS error. This is discussed further in the next section on objective verification.

3.6.2 Transient Eddy Kinetic Energy

The transient eddy kinetic energy (TEKE), defined as TEKE = $\frac{1}{2}(\overline{u'^2 + v'^2})$, is a useful measure of the energy associated with mid-latitude transient weather systems. Figure 26 shows the zonally averaged TEKE at 250hPa. The HIRES analyses and forecasts show higher values of TEKE than the CONTROL analyses and forecasts, consistent with the increased variability noted in the 500hPa geopotential height. The HIRES forecasts show good agreement with the HIRES analyses in the NH, whereas the CONTROL day 3 forecasts show a decline in the TEKE compared to their respective analyses. In the SH both HIRES and CONTROL forecasts show a decline in TEKE, but this is less marked in the HIRES forecasts.

4 Objective verification

In this section we describe the objective verification against analyses, radiosondes and surface observations (SYNOPS). Following operational practice, objective verification is performed on a 2.5° grid. The HIRES fields are first interpolated to the CONTROL wind grid and from there they are 'smoothed' to 2.5° using the same technique as used operationally. Verification against analysis was performed against the appropriate analysis: CONTROL forecasts against CONTROL analyses and HIRES forecasts against HIRES analyses. We deal with each of the variables (MSLP, temperature etc.) in turn.

4.1 Mean Sea Level Pressure

For January 1997 The RMS errors in MSLP are reduced in the extratropics by up to 6% against both analyses (Fig. 27(b) and (f)) and SYNOPS (Fig. 28)(b) and (f)). In the tropics there is an increase in the RMS error of up to 6% against analyses (Fig. 27(d)) and by a constant 3% against observations. For July there are similar improvements in RMS error in the NH extratropics for verification against analyses (Fig. 29(b)). Again the RMS errors are increased in the Tropics (Fig. 29(d)) , but also this time in the SH (Fig. 29(f)). The SH performance is degraded as a result of the error in assimilation of the south pole observation which has since been corrected (Milton and Lorrimer, 1997)

In section 3.2 we discussed the improvement in the mean errors of the extratropical MSLP fields. This improvement is also apparent in the reduced biases for verification against analyses in both January (Fig. 27 (a),(c), and (e)) and July (Fig. 29 (a),(c), and (e)).

The time series of T+48 RMS errors from the individual 21 forecasts in January and July are shown in figure 30 and figure 31 respectively. In January 1997 the HIRES has smaller RMS errors in 15 out of the 21 forecasts in the NH (Fig. 30(a)) and is worse in only 2 of the cases. In July 1997 the RMS errors in the NH are smaller for HIRES in 14 out of 21 cases (Fig. 31(a)), although improvements are not as large as in January. For the SH the RMS errors are smaller in the HIRES forecasts in half of the cases during January 1997. However, in July 1997 we see the adverse effect of the data assimilation error over the South Pole on the HIRES forecasts.

4.2 Winds

4.2.1 Verification against radiosondes

In general the HIRES has smaller RMS vector wind errors than the CONTROL for both the January (Fig. 32) and July (Fig. 33) trials. The largest improvements are to the NH upper level winds in January 1997 with a 3% improvement at T+24 (Fig. 32(a)) and a 6% improvement at T+120 (Fig. 32(b)). Degraded performance is seen in the low level tropical winds (particularly during July), and the SH RMS vector wind errors during July.

The HIRES analyses are also a better fit to the radiosonde observations than the CONTROL analyses, as shown by the RMS vector wind errors at T+00 in January 1997 (Fig. 34). A similar result is found for July.

4.2.2 Verification against AIREP's

Figure 35 shows the T+24 RMS vector wind errors and biases for verification of model winds against AIREP's. The biases are improved in all regions. In the extratropics the RMS vector wind errors are improved in HIRES between -2% and -4%. The tropical scores are worse at 200hPa. These results agree with those against radiosondes. However a lot of the AIREPS are located over the ocean, so combined with the results from the radiosondes suggest that upper level winds in HIRES are an improvement over both land and ocean when verified against observations.

Improvements in extratropical temperature verification against AIREPS is even larger, with HIRES showing reductions in RMS temperature errors of the order -8% to -10% in the NH extratropics (Fig. 36)

4.2.3 Verification against analyses

The verification of forecast winds against analyses does not show the same improvements in the extratropics as the verification against radiosondes. The extratropical winds show larger RMS vector wind errors at T+24 for HIRES in Januray 1997 (Fig. 37(a) and (e)), but have smaller errors at T+120 in the NH and show a neutral change in the SH. As with all other fields the SH RMS vector wind errors in July are worse in HIRES, whilst the NH winds are worse at T+24 and show a neutral impact at T+120 (not shown). In the tropics the RMS vector wind errors in low level winds are worse at all time ranges in both January ((Fig. 37(c) and (d)) and July (not shown)

One possible explanation for larger RMS vector wind errors for T+24 wind forecasts (vs analyses) in HIRES may be the increased variance in both HIRES forecasts and analyses. Equation (2) shows that increasing variance without increasing the correlation term, r, does increase the MSE. However, without calculating the additional variance and correlation terms in equation (2) this remains speculation. Unfortunately these additional terms are not available from the current verification system. A closer fit of HIRES analyses to observations could be another possible explanation for the larger error growth rate at early forecast ranges in HIRES when verified against analyses.

4.3 Geopotential Height

Firstly, we note that the tropical RMS errors are uniformly worse in HIRES for geopotential height in both January (Fig. 38(c) and (d)) and July (Fig. 39(c) and (d)) when verified against analyses. This is linked to the increased cold bias in the tropical upper troposphere in HIRES forecasts.

In January 1997 the RMS errors (vs analyses) for the extratropical height fields are improved by 4-8% at both T+24 and T+120 in both the NH(Fig. 38(a) and (b)) and SH (Fig. 38(e) and (f)). A similar improvement is seen in the verification for the NH height field in July (Fig. 39(a) and (b)). However the SH RMS errors are considerably worse at both time ranges. Again this has been traced to the problems discovered with the assimilation of the surface pressure from the South Pole station.

4.4 Near surface weather elements

4.4.1 1.5m temperatures

Against analyses the 1.5m temperature RMS errors (Fig. 40(a), (c) and (e)) for January 1997 improve in all regions. At T+120 there are reductions of 6% , 3% and 7% in the NH, tropics and SH respectively. Against observations reductions of 2.5% are still seen in the NH (Fig. 40(b)), but the tropics show a consistent increase in RMSE of 2-3% (Fig. 40(d)) and at T+120 there is an increase of 3% in the SH(Fig. 40(f)).

4.4.2 10m Winds

Against observations the 10m wind bias (Fig. 41(a), (c) and (e)) shows a consistent weakening of the wind in all areas in January 1997. This is beneficial in the tropics, where the positive bias reduces by about $0.025 \mathrm{ms}^{-1}$. However, in the extratropics the change is detrimental making the negative biases worse. The 10m RMS vector wind errors (Fig. 41(b), (d) and (f)) show improvements of 2% in all areas.

4.5 Skill and the NWP index

A drawback of using RMS based measures of forecast accuracy is that the RMS error can be increased/decreased simply by increasing/decreasing the variance of the forecasts or verifying analyses/observations (see equation (2)). It was for this reason that a new NWP index was devised based upon a skill score (SS), which is the MSE normalized by a measure of persistence in the verifying analyses

$$\mathrm{SS} = 1 - \mathrm{MSE(Forecast)/MSE(Persistence)} \tag{3}$$

The skill score is less prone to fluctuations in variance (and hence RMS error) associated either with different synoptic regimes or changes in variability due to model changes. A perfect forecast has a skill score of 1. A score of 0 implies our forecasts are no better than those achieved by persisting the analysis fields.

The impact of enhanced resolution on the components making up the skill based NWP index are summarized in Appendix A and B. The wind verification is a good example of the effect

of increased variance on RMS errors and skill. At T+24 the RMS vector wind error is larger in HIRES, at 5.6 ms^{-1} compared to only 5.4 ms^{-1} in the CONTROL (see entries (8) and (5) in the table in Appendix A). However, the RMS persistence error for HIRES is also higher than in CONTROL (see entries (9) and (6)). As a consequence the *skill* of HIRES is identical to that of CONTROL (see entries (10) and (7) which show the index weight multiplied by the skill).

Figures 42 and 43 also summarise the impact on the skill (as given in equation 3) of the main NWP index components for the January and July 1997 trials.

For January 1997 HIRES is clearly more skilful than CONTROL in most areas and for most fields (although improvements in the 250hPa winds are disappointingly small). The exception is the 850 hPa tropical winds which appear to deteriorate with forecast range. In most cases the increases in skill are only significant at later forecast ranges. Unfortunately, these later forecast ranges only have a small weighting in the NWP index (see Appendix A). The weighted mean skill (over all NWP index components) is 80.75 for the CONTROL and 81.29 for the HIRES. It is not possible to translate this directly into a value for the *operational* NWP index as this includes 12 month running means and a normalisation to a base year. However, we estimate that using HIRES in place of CONTROL would lead to an increase in the *operational* NWP index of 1.4% from 107.3 to 108.8.

For July we see that the NH MSLP scores are improved at all ranges and the height fields are improved at T+24 and neutral at T+48 and T+72. As for January the skill for 850hPa tropical winds show a steady deterioration with forecast range whilst the 250hPa tropical winds are a small improvement. The skill scores for the SH are all worse. Again we attribute most of this deterioration to the incorrect assimilation of the south pole observation. This period is currently being rerun with this change corrected and initial results show that the impact of enhanced resolution on SH performance in July is largely neutral as measured by the NWP index components (Milton and Lorrimer, 1997).

4.6 Overall Summary of RMS Errors

Finally, as a gross measure of performance we have conducted a simple count of the number of occasions the RMS errors for HIRES are improved relative to the CONTROL for all fields, all regions and all measures of truth (i.e analyses and observations) for the January 1997 (Appendix C) and July 1997 (Appendix D) parallel trials. In order to be considered better/worse the difference in RMS error between HIRES and CONTROL must exceed a threshold of 1%.

This basically confirms the results of the previous sections; Area 2 and the NH are improved in both January and July. For example, in January 1997 verification against analyses shows 132 RMS scores are better in HIRES, 30 are neutral, and only 46 are worse. The tropics are uniformly worse as is the SH in July (problems with data assimilation error over S.Pole).

5 Subjective Assessment

5.1 Method of assessment

Each daily 12UTC model run for CONTROL and HIRES was examined for January and July trials. The following fields were assessed; Mean Sea Level Pressure (MSLP), 500hPa Heights,

250hPa isotachs and accumulated precipitation.

5.2 January Trial

5.2.1 Overall Performance

The subjective performance for the extratropics is summarised in Appendix E which gives a count of the number of occasions HIRES was considered a better forecast than the CONTROL. On balance the HIRES is either better than CONTROL or the changes are neutral.

5.2.2 Discussion

Northern Hemisphere Mean Sea Level Pressure
Differences between HIRES and CONTROL forecasts at T+24 were small and for the most part insignificant. In 17 of the 20 cases the changes were considered neutral, with the HIRES preferred in 1 run and the CONTROL in 2. Even these were marginal cases (e.g. CONTROL was preferred merely because the HIRES had cyclonic development off Newfoundland 4-6hPa too deep). By T+120 forecast differences were occasionally as large as 24hPa over small areas, but still mostly a result of position and/or depth of individual systems rather than large changes in evolution. An example of an improvement in the HIRES is shown in Figure 44 where the HIRES has a deep Atlantic depression at 30W better positioned and with a better depth than CONTROL. Figure 45 is a counter example which shows the HIRES has overdeepened a low in the base of a short wave trough at 25°W.

Southern Hemisphere Mean Sea Level Pressure
Larger differences were found in the SH, but the overall signal was similar to that in the NH, with no preference for the majority (16) of forecast runs at T+24 and the remaining 4 divided equally between CONTROL and HIRES. By T+72 roughly twice as many HIRES forecasts were preferred as CONTROL (see Appendix E). Some minor differences in evolution did occur at longer range, such as the development of an erroneous secondary low pressure centre in HIRES where the CONTROL had a single centre. Figure 46 shows an example of this at T+72 for low pressure systems to the sout east of New Zealand, and in this case the HIRES was incorrect. Figure 47 however is a case where the HIRES produced a better forecast than the CONTROL in having a secondary depression less well developed than the CONTROL, and consequently a much weaker and more accurate zonal flow between Australia and South America.

Tropical Cyclones
A number of SH tropical cyclones were active during the period: Drena, Evan, 18S and Pancho in the Australian Basin and Gretelle and Iletta in the south-west Indian basin. The HIRES model forecasts produced deeper centres for all of these systems often by 8-12hPa at T+48. However, the analyses were very similar. Comparing the forecast intensities with the analyses therefore showed increased errors for the HIRES. However, relative to the central pressures given in the tropical cyclone advisories the HIRES forecast central pressures verified much better (central pressure estimated from wind speeds when none given).

For cyclone Evan the HIRES developed an intense system a day and a half too early and one or two of the other storms were kept as intense features in the forecasts a couple of days too long. Tropical cyclone Evan is more intense in the HIRES forecast(Fig. 49) than in the CONTROL (Fig. 48), with a central pressure of 980 hPa when the advisory was giving 975 hPa and the

CONTROL forecast 998 hPa. The forecast positions were also generally better in the HIRES forecasts. For cyclone Iletta the CONTROL's forecast position was around 300Km better on a couple of runs. Overall, though, the HIRES MSLP forecasts were seen as giving better guidance than the CONTROL.

5.3 July Trial

5.3.1 Overall Performance

The subjective performance is summarised in Appendix F. On balance the HIRES is mostly a neutral impact compared to CONTROL. The SH performance is worse in HIRES, but as for the objective verification this is mostly due to problems with the incorrect assimilation of surface pressure over the pole.

5.3.2 Discussion

NH Mean Sea Level Pressure
Differences between the HIRES and CONTROL forecasts at T+24 were insignificant, only by T+96 had differences grown sufficiently to allow a judgement on overall accuracy/preference to be made. By T+144 forecast differences were occasionally as much as 14hPa over small areas, but as a result of position or depth of individual systems, rather than evolution. An example of an improvement provided by the HIRES is shown in figure 50 where the HIRES forecast at T+96 had correctly positioned a shallow depression over Nova Scotia compared to the CONTROL which had forecast a ridge.

500hPa Height
A neutral signal, with no significant differences for nearly all runs at T+24. Most T+48 forecasts also had only small differences, with the HIRES preferred in just two runs and the operational also only in two, the rest neutral (Appendix F).

SH Mean Sea Level Pressure
Apart from large errors over the Antarctic continent, the most obvious error in the HIRES is a tendency to over-deepen depressions, especially at lower latitudes i.e. 30S-35S.

Tropics
There were a number of active northern hemisphere tropical cyclones in the period i.e. Dolores, Enrique and Felicia in the north-east Pacific, Rosie in the north-west Pacific and Ana, Bill, Claudette and Danny in the North Atlantic/Gulf of Mexico. All of the last four storms however had tropical characteristics for only a short time and were relatively weak, with no significant difference between the CONTROL and HIRES analyses or forecasts. On the majority of days during the life of 'Dolores', Enrique and Felicia the HIRES analyses had the central pressure around 4hPa lower (better) than the CONTROL analysis, and often the HIRES forecasts were also deeper.

We give an example from forecasts of tropical cyclone Rosie. On the 9th July run at T+144 (VT 15th) the HIRES produced a 996hPa low over the northwest Pacific. The 10th July run then had this development by T+120 (VT 15th) on both CONTROL and HIRES, although 12hPa deeper in the HIRES. Later runs continued with this development, at shorter range, but with the CONTROL and HIRES very similar in both depth and position. Eventually, by the 18th a

tropical depression (later to become typhoon 'Rosie') did develop in the general area, so both the CONTROL and HIRES had been 3 days too early, with the HIRES a little worse in this respect. 'Rosie' did not actually reach named stength until the 20th. The 16th July HIRES run had 'Rosie' 8hPa too deep at T+72, (and similar position to CONTROL.) but the pressure at T+96 (VT 20th) for the HIRES verified well against the central pressure derived from wind speeds given in the advisories. This was 16hPa deeper (better) than the CONTROL forecast. This is shown in figure 51 and figure 52. The signal was similar at T+120 but the CONTROL position verified slightly better by about 100 nautical miles. At T+144 the CONTROL position was again better, by about 140 nautical miles, but with a central pressure of 996hPa against 976hPa on the HIRES. By this time 'Rosie' was a super typhoon with an estimated central pressure of only 898 hPa.

The HIRES has an increased tendency, relative to the CONTROL, of developing tropical cyclones somewhat too deep and too early but once a storm has reached a more developed stage the lower pressures of the HIRES appear better, especially when verified against advisory information rather than analyses. The subjective verification of cyclone tracks showed a more mixed signal, but overall the HIRES' handling of tropical cyclones is preferred.

5.4 Conclusions from subjective assessment

Overall, there is a small improvement in forecast accuracy in mid-latitudes for HIRES, particularly in January. The most significant impact in the Tropics are forecasts of deeper tropical cyclones in HIRES in both January and July, which appear to be largely beneficial. For many of the runs the differences were quite small at early forecast ranges and often small improvements in verification of some individual systems were balanced by small detriments in others. When a particular forecast was judged as being the more accurate at T+72 it was generally found this was still the case at longer ranges. Although the 250hPa winds were not examined in as much detail, it would appear subjectively that the overall impact of the HIRES on accuracy was at worst neutral and probably of slight benefit over the CONTROL forecasts.

In July there was a clear detriment for the SH, partly due to the errors in the assimilation over Antarctica (now corrected). However, the HIRES forecasts did show a tendency for extratropical cyclones to be deeper in the SH.

6 Summary

The main advantages and disadvantages of using enhanced resolution in the global UM are summarised below.

1. Benefits

   - Reduced Bias and RMS errors for extratropical MSLP at most time ranges for verification against analyses and SYNOPS (6-8% improvement in NH).
   - Reduced Bias and RMS errors for geopotential height at all time ranges
   - Reduced RMS error for winds at all forecast ranges when verified against radiosondes and AIREP's.
   - Reductions in RMS vector wind errors (verifying against analyses) in the extratropics at later forecast ranges of T+72 onwards in January.
   - Subjective assessment suggests more realistic tropical cyclones with deeper centres.
   - Reduction of systematic errors in the global UM, noteably
     - Reduced upper tropospheric temperature bias and improved thermal balance in the extratropics.
     - Reduced upper tropospheric moist bias in tropics and extratropics.
     - Reduced westerly wind bias and improved momentum balance in the extratropics.
     - Reduced errors in the jets in both NH and SH.
     - Increased precipitation and diabatic heating in the stormtracks.

2. Disadvantages.

   - Upper tropical tropospheric temperature bias and RMS error are worse in HIRES.
   - Increased drying in the tropical mid-troposphere.
   - Low level tropical wind RMS vector wind errors are worse in the HIRES at longer time ranges.
   - Increased RMS errors for winds at early forecast ranges when verified against analyses.
   - SH RMS errors are worse in July (SH winter) in most variables (partly explained by known error in the data assimilation since corrected).
   - Numerical instability at longer timesteps.

The winter and summer trials show that enhanced resolution is in general an improvement over the current operational resolution. Many of the systematic errors in the current operational UM are reduced. Most noteably the upper tropospheric cold and moist biases, MSLP errors over North America and Europe, and errors in the winds at jet level and in the stratosphere. From a dynamical/physical viewpoint the model appears to be in better thermal balance in the extratropics in HIRES both at the tropopause and in the stormtracks. We believe this reflects a more accurate simulation of the vertical and horizontal transports of temperature and moisture. Similar improvements can be seen in the mid-latitude momentum balance, with more accurate fluxes of momentum from the dynamics and reductions in the extratropical westerly wind bias.

Although the overall increase in the NWP index for January is only a modest 1.4%, some of the individual components do show larger increases. For example the NH MSLP RMSE scores are improved by up to 6-8% in both January and July. However, the largest impacts come at later forecast ranges, which have smaller weights in the NWP index. One dissapointing feature are the increases in RMS vector wind errors for T+24 verification against analyses. This is surprising given the large improvements in upper level winds for verification against radiosondes and AIREP's. The use of skill rather than RMS measures suggests that some of the detriment in RMS measures can be attributed to increased variability in HIRES analyses and forecasts (see transient eddy kinetic energies). In addition we also note that the HIRES analyses provide a much closer fit to the observations than the CONTROL analyses.

On the negative side the tropical simulation appears to have become worse, with an increased cold bias in the upper tropical troposphere and increased RMS errors in temperatures and low level winds. The latter have a negative impact on the overall NWP index. Subjective assessment of the tropical cyclones shows much more intense systems with more realistic looking wind and precipitation structures. In general the central pressures of the HIRES tropical cyclones agreed more closely with the tropical cyclone advisories, although the model often showed a tendency to develop systems one or two days too early.

The SH RMS errors in summer(July) were a concern. However, we believe most of the detriment is caused by the incorrect assimilation of surface pressure over Antarctica. There is still some suggestion that there is increased variability in the HIRES with extratropical cyclones being deeper.

7 Recommendation for future work

The tests described in this paper were carried out with virtually no retuning of the parametrizations or assimilation. Given the diagnostic evidence presented in this paper we can suggest a number of areas where further sensitivity studies could be carried out. Main concerns is the degraded tropical performance, apparently small benefits to upper level wind forecasts (only when verified against analyses!), and the numerical instabilities encountered when running with longer timestep.

1. *Tropics - Convection* The role of convection in the Tropics at enhanced resolution deserves further consideration. The results from the momentum balance diagnostics suggest that changes in the convective momentum transports may play a large role in determining the upper level winds. Also the mid tropospheric drying in the Tropics is an outstanding error in the UM which may be linked to convection. This error is worse at enhanced resolution. The increase in the cold bias in the upper tropical troposphere appears to be associated with changes in the cloud longwave forcing associated with reducing layer and convective cloud. Interestingly a similar reduction in upper tropospheric cloud and humidity is beneficial in the extratropics. Given the lack of observational data on upper tropospheric cloud fractions and cloud radiative properties it seems unlikely that this error will be improved in the short term.

2. *Extratropical Winds - Gravity Wave Drag (GWD)* Past experience has shown that apparently small changes to the momentum sink provided by GWD can have large impacts upon the mid-latitude flow and upper level winds on the 5-day timescale. We recommend that some sensitivity experiments are carried out with the GWD scheme in order to optimize the tuneable constants within the uncertainties.

3. *Numerical Instability at longer timesteps* Initial tests have shown numerical instability in the enhanced resolution model can be removed by either (i) reducing the timestep from 20 to 15 minutes or (ii) running without convective momentum transports. We recommend a more comprehensive study of the role of convective momentum transports at enhanced resolution. This will also address some of the concerns raised in point 1.

4. *Upper tropospheric moisture* One of the apparent benefits of the enhanced resolution is a reduction in upper tropospheric moist bias. However there are still large uncertainties as to what the correct values of upper tropospheric moisture are. More diagnostic work is required to validate the moisture fields. One possibility is comparison with the TOVS water vapour channels (see paper by Chen et. al., 1996).

8 Reference

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Appendix

A Parallel suite estimate of impact on weighted mean skill 970102 to 970122

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
NH	PMSL	T+24	10	192.9	750.2	9.34	182.7	748.2	9.40	0.06
NH	PMSL	T+48	8	318.7	1011.0	7.21	300.6	1007.1	7.29	0.08
NH	PMSL	T+72	6	462.3	1110.3	4.96	448.2	1106.7	5.02	0.06
NH	PMSL	T+96	4	643.8	1146.0	2.74	630.8	1141.5	2.78	0.04
NH	PMSL	T+120	4	820.8	1165.9	2.02	799.1	1160.5	2.10	0.09
NH	H500	T+24	6	15.2	73.1	5.74	14.8	73.6	5.76	0.02
NH	H500	T+48	4	28.3	104.5	3.71	27.0	104.9	3.73	0.03
NH	H500	T+72	2	44.6	119.5	1.72	42.8	119.7	1.74	0.02
NH	W250	T+24	12	5.4	19.0	11.02	5.6	19.4	11.02	0.00
Tropics	W850	T+24	5	2.3	3.3	2.60	2.4	3.5	2.65	0.05
Tropics	W850	T+48	3	3.1	4.5	1.60	3.3	4.7	1.53	-0.06
Tropics	W850	T+72	2	3.6	4.9	0.93	3.8	5.1	0.87	-0.06
Tropics	W250	T+24	6	4.0	7.0	4.10	4.0	7.2	4.12	0.03
SH	PMSL	T+24	5	219.2	616.2	4.37	228.2	630.8	4.35	-0.02
SH	PMSL	T+48	4	342.8	793.2	3.25	346.3	807.7	3.26	0.01
SH	PMSL	T+72	3	452.9	890.6	2.22	448.9	901.0	2.26	0.03
SH	PMSL	T+96	2	563.0	937.7	1.28	549.6	948.8	1.33	0.05
SH	PMSL	T+120	2	669.6	970.0	1.05	652.4	981.6	1.12	0.07
SH	H500	T+24	3	18.3	70.3	2.80	18.2	71.8	2.81	0.01
SH	H500	T+48	2	32.8	93.2	1.75	32.5	94.8	1.77	0.01
SH	H500	T+72	1	47.2	105.6	0.80	46.3	107.0	0.81	0.01
SH	W250	T+24	6	5.2	19.3	5.56	5.3	19.9	5.57	0.01

Total weight: 100
CONTROL index: 80.75
HIRES index: 81.29

Notes:
(1) Area of verification. Limits of Tropics are at 20 degrees.
(2) Field of verification.
(3) VT of verification.
(4) Weight used in index, W_i .
(5) Control RMS for this period.
(6) Control persistence RMS for this period.
(7) Control contribution to mean (W_i * skill)
(8) Test RMS for this period.
(9) Test persistence RMS for this period.
(10) Test contribution to mean (W_i * skill)
(11) Change in contribution to index ((10)-(7))

Appendix

B Parallel suite estimate of impact on weighted mean skill 970702 to 970722

(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
NH	PMSL	T+24	10	151.3	358.2	8.22	145.8	356.9	8.33	0.11
NH	PMSL	T+48	8	234.3	519.4	6.37	223.7	518.0	6.51	0.14
NH	PMSL	T+72	6	301.9	580.8	4.38	288.5	579.9	4.51	0.14
NH	PMSL	T+96	4	360.9	610.6	2.60	350.3	609.8	2.68	0.08
NH	PMSL	T+120	4	429.6	623.1	2.10	415.6	622.4	2.22	0.12
NH	H500	T+24	6	11.5	36.2	5.39	11.3	36.5	5.43	0.03
NH	H500	T+48	4	20.3	55.5	3.46	20.4	55.7	3.46	0.00
NH	H500	T+72	2	29.6	65.6	1.59	29.7	65.6	1.59	0.00
NH	W250	T+24	12	4.6	13.3	10.56	4.7 1	3.7	10.57	0.00
Tropics	W850	T+24	5	2.4	3.2	2.19	2.5	3.4	2.19	0.00
Tropics	W850	T+48	3	3.2	4.2	1.26	3.4	4.3	1.17	-0.09
Tropics	W850	T+72	2	3.7	4.5	0.68	4.0	4.7	0.57	-0.10
Tropics	W250	T+24	6	3.6	6.2	3.97	3.8	6.5	4.00	0.03
SH	PMSL	T+24	5	278.2	823.8	4.43	331.8	849.4	4.24	-0.19
SH	PMSL	T+48	4	451.6	1138.7	3.37	521.5	1174.2	3.21	-0.16
SH	PMSL	T+72	3	593.7	1317.2	2.39	678.3	1358.9	2.25	-0.14
SH	PMSL	T+96	2	731.5	1423.6	1.47	828.0	1468.9	1.36	-0.11
SH	PMSL	T+120	2	869.1	1454.2	1.29	964.5	1496.5	1.17	-0.12
SH	H500	T+24	3	21.4	86.2	2.82	23.9	87.0	2.77	-0.04
SH	H500	T+48	2	39.6	125.5	1.80	45.5	126.2	1.74	-0.06
SH	H500	T+72	1	55.5	147.8	0.86	64.1	148.3	0.81	-0.05
SH	W250	T+24	6	5.4	20.8	5.60	6.0	21.5	5.53	-0.07

Total weight: 100
CONTROL index: 76.80
HIRES index: 76.30

Notes:
(1) Area of verification. Limits of Tropics are at 20 degrees.
(2) Field of verification.
(3) VT of verification.
(4) Weight used in index, W_i .
(5) Control RMS for this period.
(6) Control persistence RMS for this period.
(7) Control contribution to mean (W_i * skill)
(8) Test RMS for this period.
(9) Test persistence RMS for this period.
(10) Test contribution to mean (W_i * skill)
(11) Change in contribution to index ((10)-(7))

Appendix

C Count of the number of RMS scores improved in January 1997 HIRES trial

Verification against analyses

	Better	Neutral	Worse
Area 2	132	30	46
NH	116	32	60
Tropics	42	27	139
SH	61	46	101
Total	351	135	346

Verification against Radiosondes

	Better	Neutral	Worse
Area 2	102	18	79
NH	119	14	67
Tropics	56	28	116
SH	157	31	12
Total	435	91	274

Verification against Synops

	Better	Neutral	Worse
Area 2	4	9	11
NH	17	3	4
Tropics	4	4	16
SH	15	2	7
Total	40	18	38

Appendix

D Count of the number of RMS scores improved in July 1997 HIRES trial

Verification against analyses

	Better	Neutral	Worse
Area 2	96	24	30
NH	57	36	57
Tropics	22	18	110
SH	2	7	141
Total	177	85	338

Verification against radiosondes

	Better	Neutral	Worse
Area 2	64	29	57
NH	58	40	52
Tropics	32	34	84
SH	47	17	86
Total	201	120	279

Appendix

E Subjective assessment of HIRES forecasts for January 1997 trial

Mean Sea Level Pressure at T+72

	CONTROL BETTER	NEUTRAL	HIRES.BETTER
N.HEMISPHERE	4	8	8
S.HEMISPHERE	4	7	9

500hPa geopotential height at T+24

	CONTROL BETTER	NEUTRAL	HIRES.BETTER
N.HEMISPHERE	3	14	3
S.HEMISPHERE	0	16	4

500hPa geopotential height at T+72

	CONTROL BETTER	NEUTRAL	HIRES.BETTER
N.HEMISPHERE	4	8	8
S.HEMISPHERE	2	15	3

Appendix

F Subjective assesment of HIRES forecasts for July 1997 trial

Mean Sea Level Pressure at T+48

	CONTROL BETTER	NEUTRAL	HIRES.BETTER
N.HEMISPHERE	0	13	2
S.HEMISPHERE	3	8	0

Mean Sea Level Pressure at T+96

	CONTROL BETTER	NEUTRAL	HIRES.BETTER
N.HEMISPHERE	1	10	4
S.HEMISPHERE	10	1	0

500hPa geopotential height at T+48

	CONTROL BETTER	NEUTRAL	HIRES.BETTER
N.HEMISPHERE	2	11	2
S.HEMISPHERE	8	3	0

500hPa geopotential height at T+96

	CONTROL BETTER	NEUTRAL	HIRES.BETTER
N.HEMISPHERE	2	10	3
S.HEMISPHERE	8	3	0

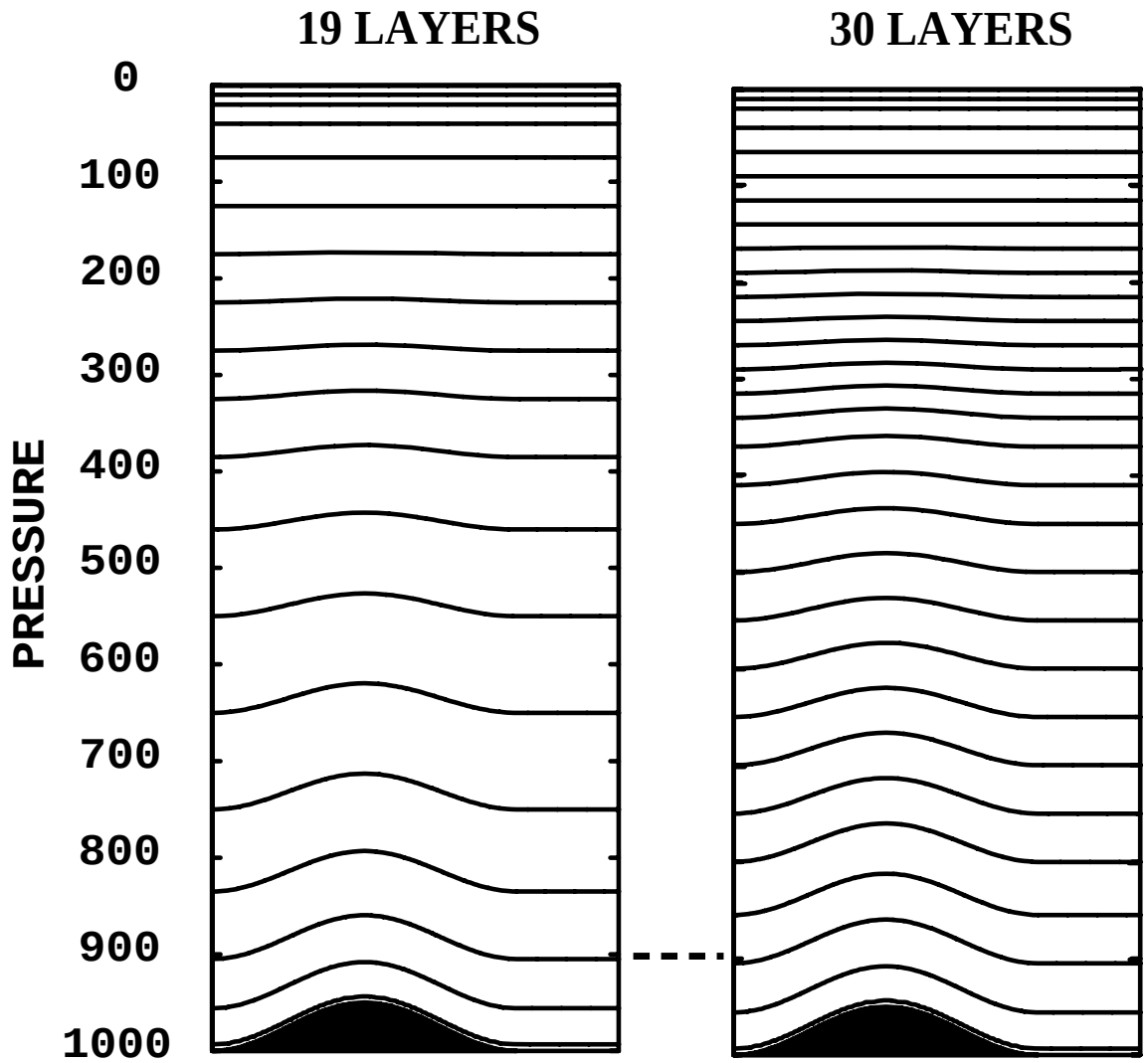

Figure 1: Changes to model resolution

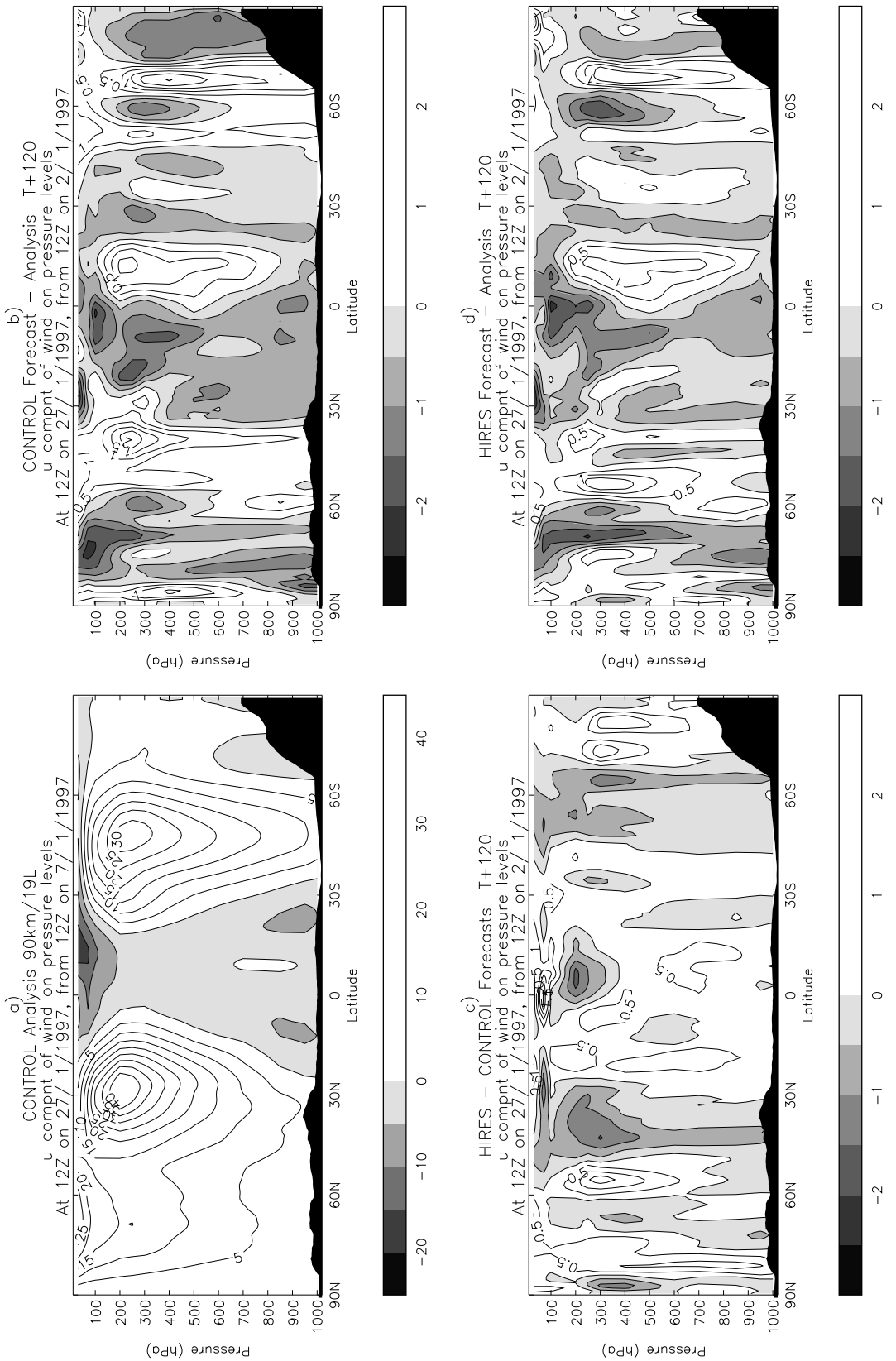

Figure 2: January 1997 zonal average zonal wind a) CONTROL analysis b) CONTROL Forecast - Analysis T+120, c) HIRES - CONTROL Forecasts at T+120 d) HIRES Forecast - Analysis T+120.

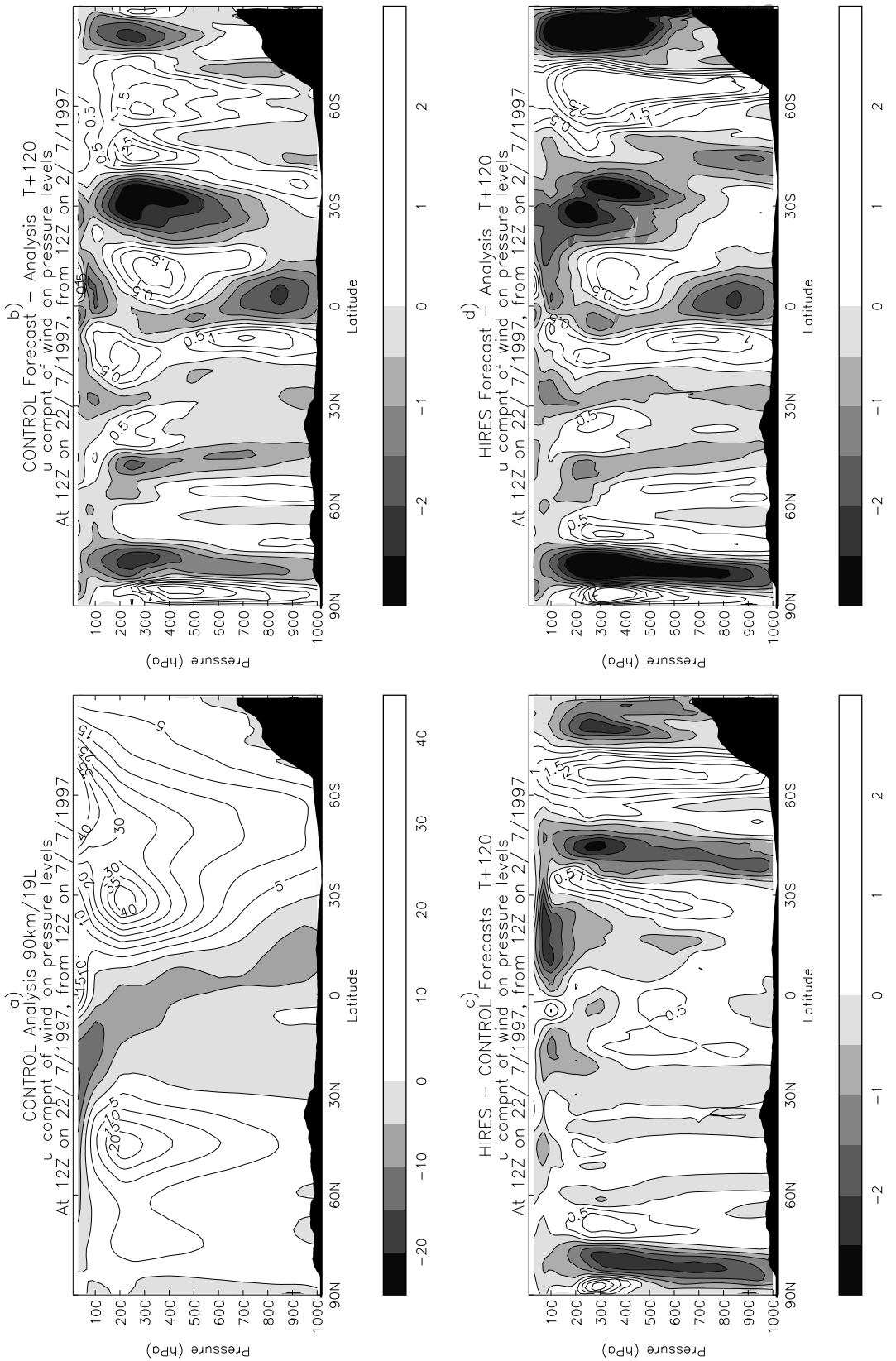

Figure 3: July 1997 zonal average zonal wind a) CONTROL analysis b) CONTROL Forecast - Analysis T+120, c) HIRES - CONTROL Forecasts at T+120 d) HIRES Forecast - Analysis T+120.

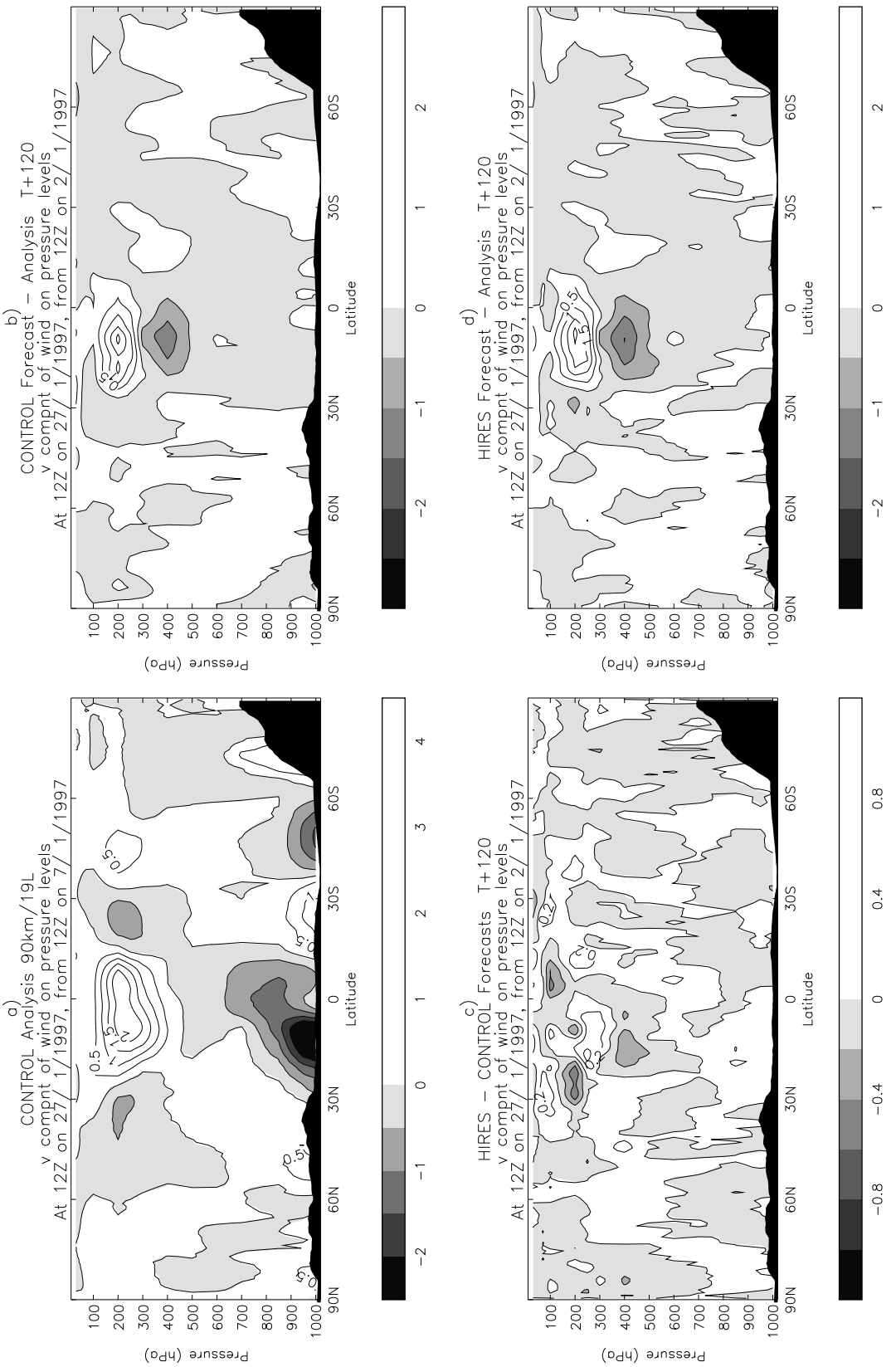

Figure 4: January 1997 zonal average meridional wind a) CONTROL analysis b) CONTROL Forecast - Analysis T+120, c) HIRES - CONTROL Forecasts at T+120 d) HIRES Forecast - Analysis T+120.

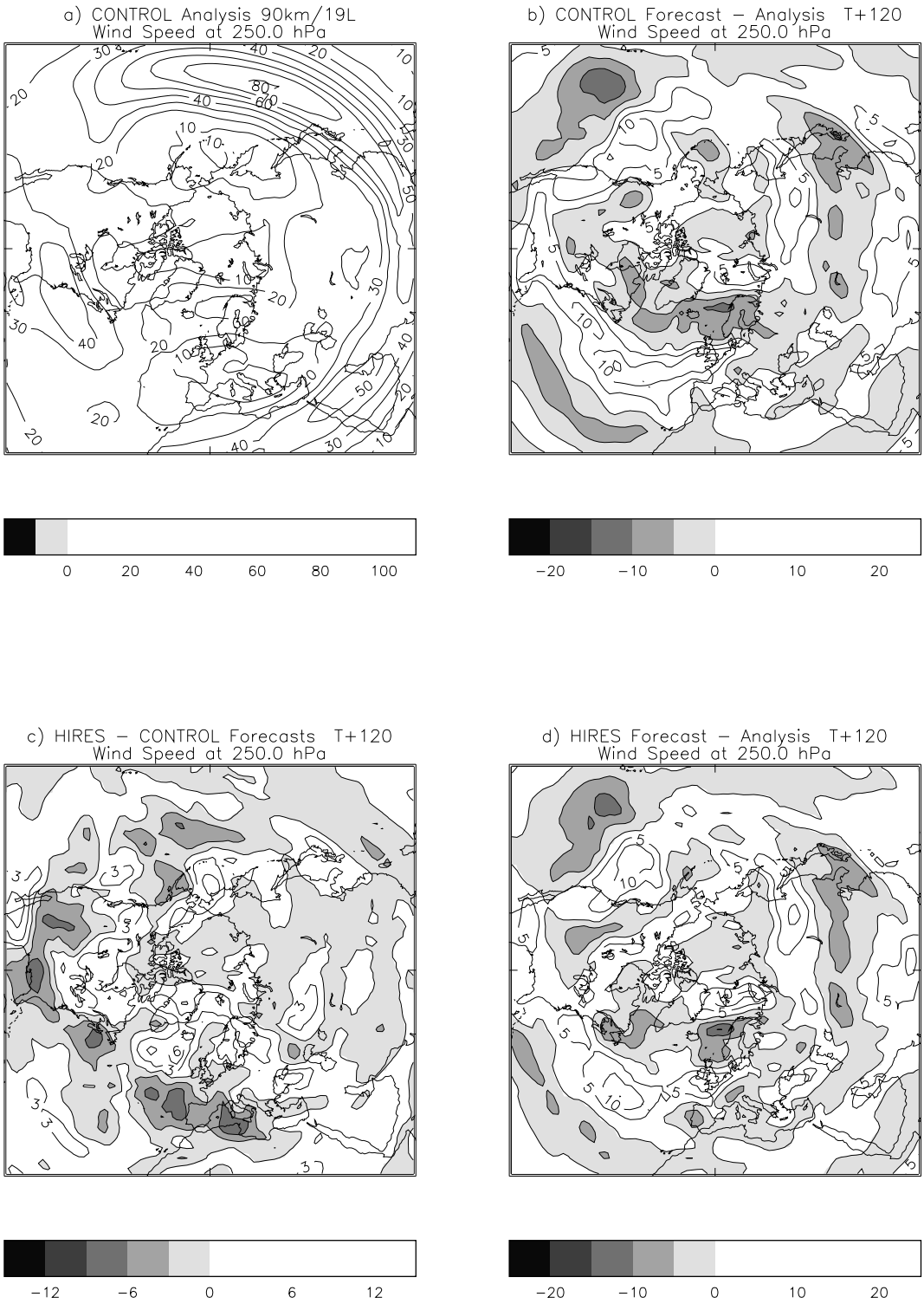

Figure 5: Wind Speed at 250hPa during January 1997 for a) CONTROL analysis b) CONTROL Forecast - Analysis T+120, c) HIRES - CONTROL Forecasts at T+120 d) HIRES Forecast - Analysis T+120.

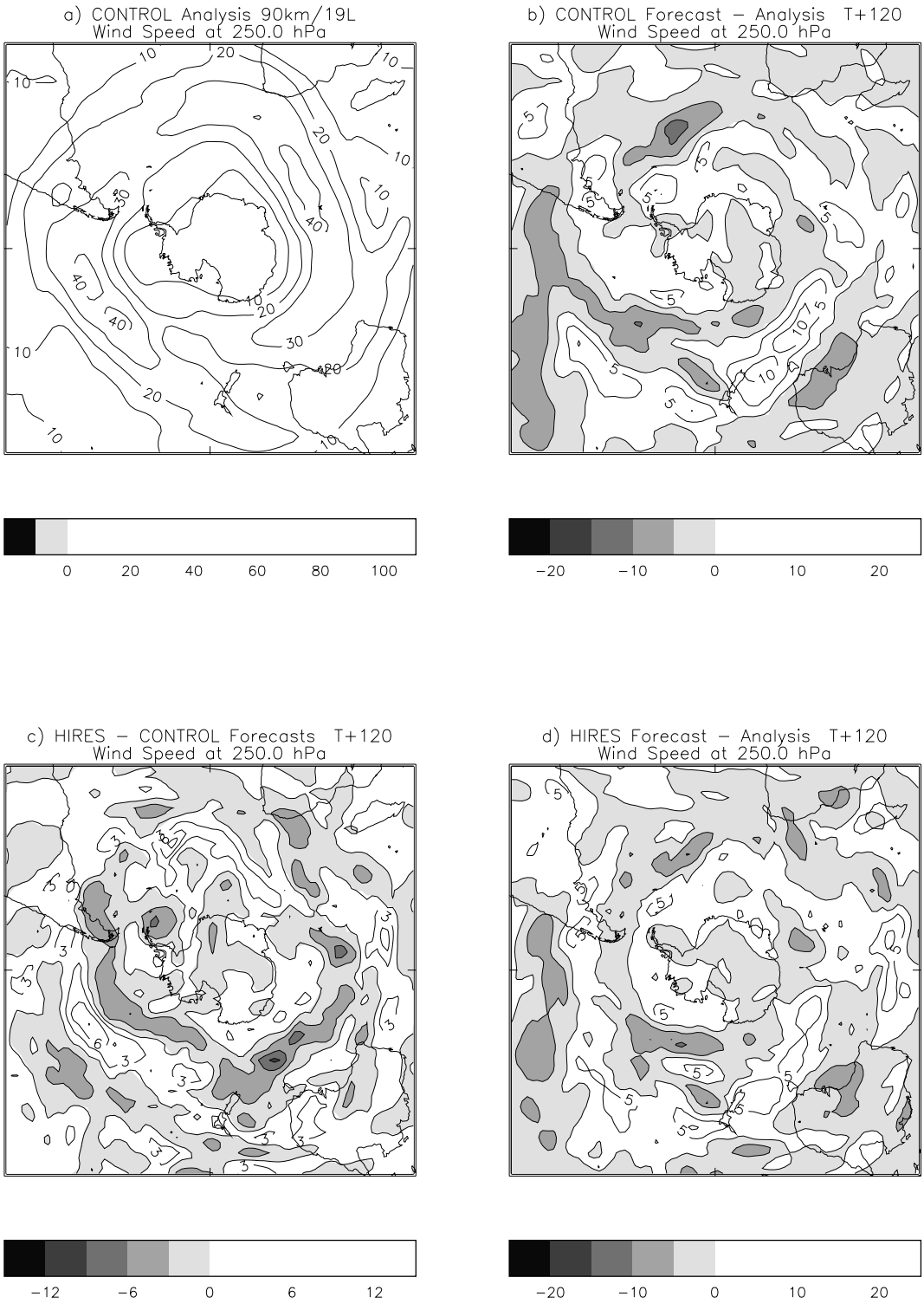

Figure 6: As Figure 5, but for the Southern Hemisphere.

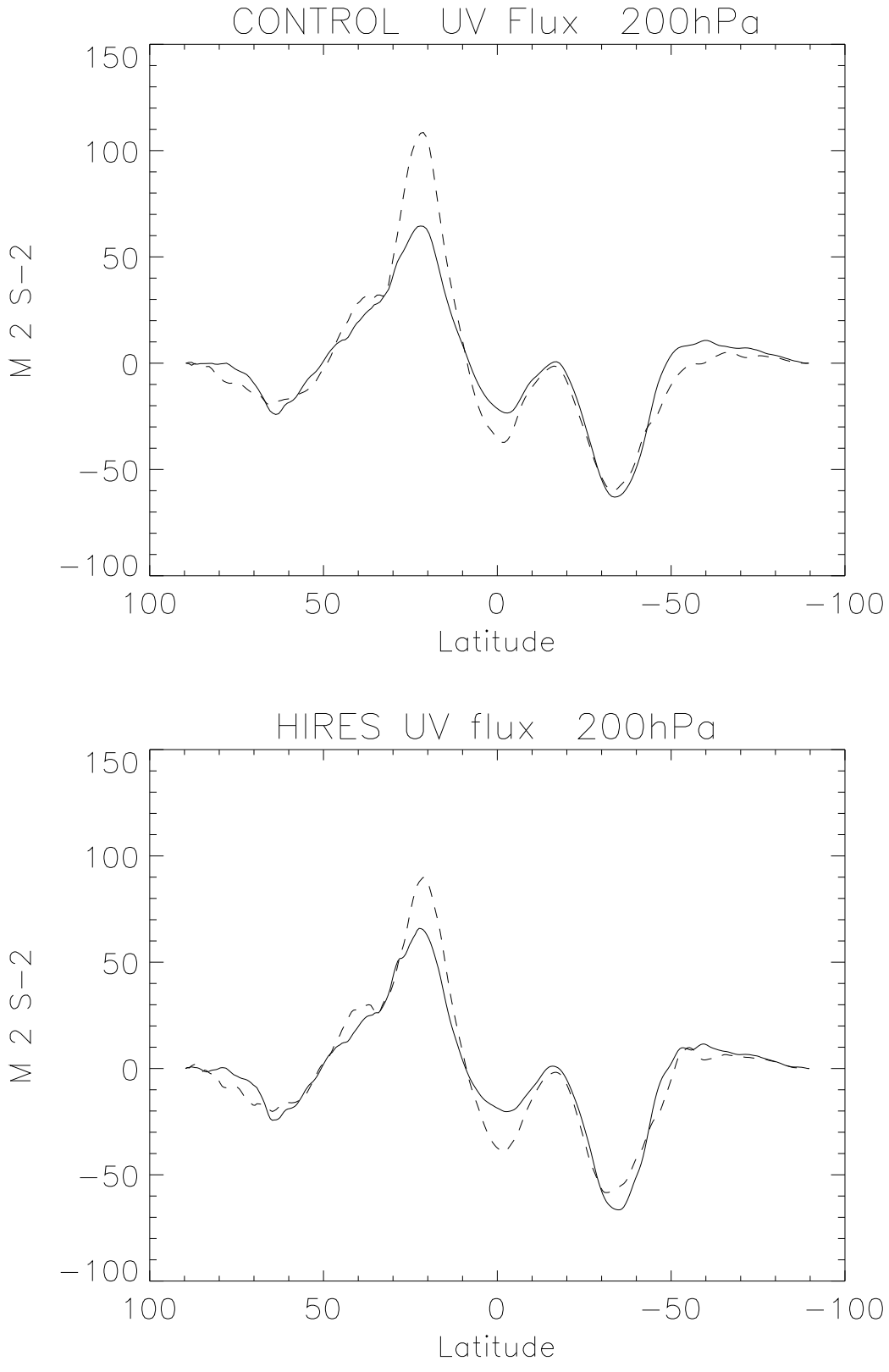

Figure 7: Total northward momentum flux during January 1997 for CONTROL (top panel) and HIRES (lower panel) showing momentum flux from analyses and day 3 forecasts.

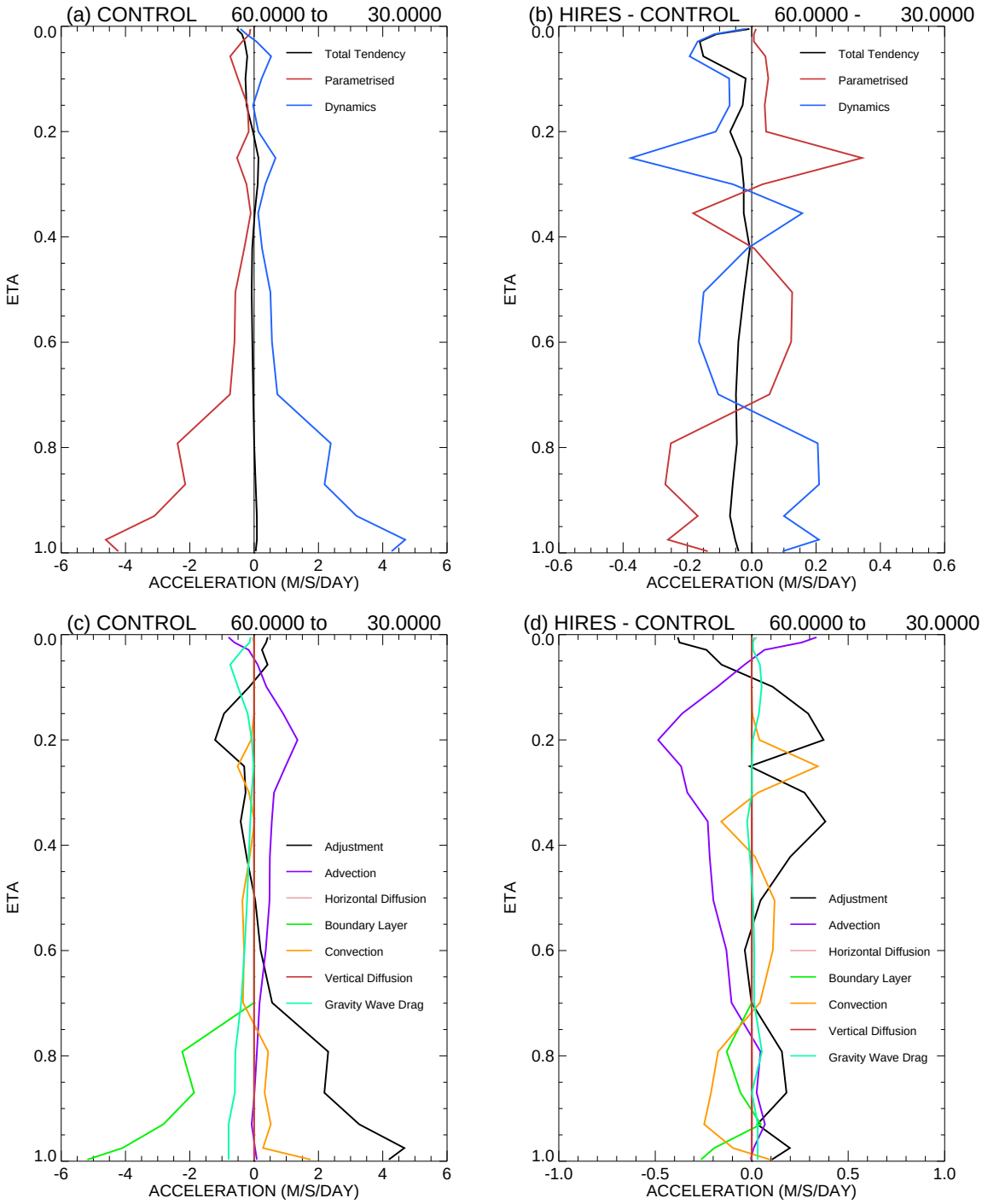

Figure 8: January 1997 Zonally averaged zonal momentum balance averaged over first 24 hours of forecasts for latitude band 60N-30N. a) CONTROL forecasts showing total tendency, dynamical and parametrized tendencies,b) as a) but for CONTROL - HIRES Difference. c) and d) as a) and b) but showing individual contributions to tne zonal momentum balance.

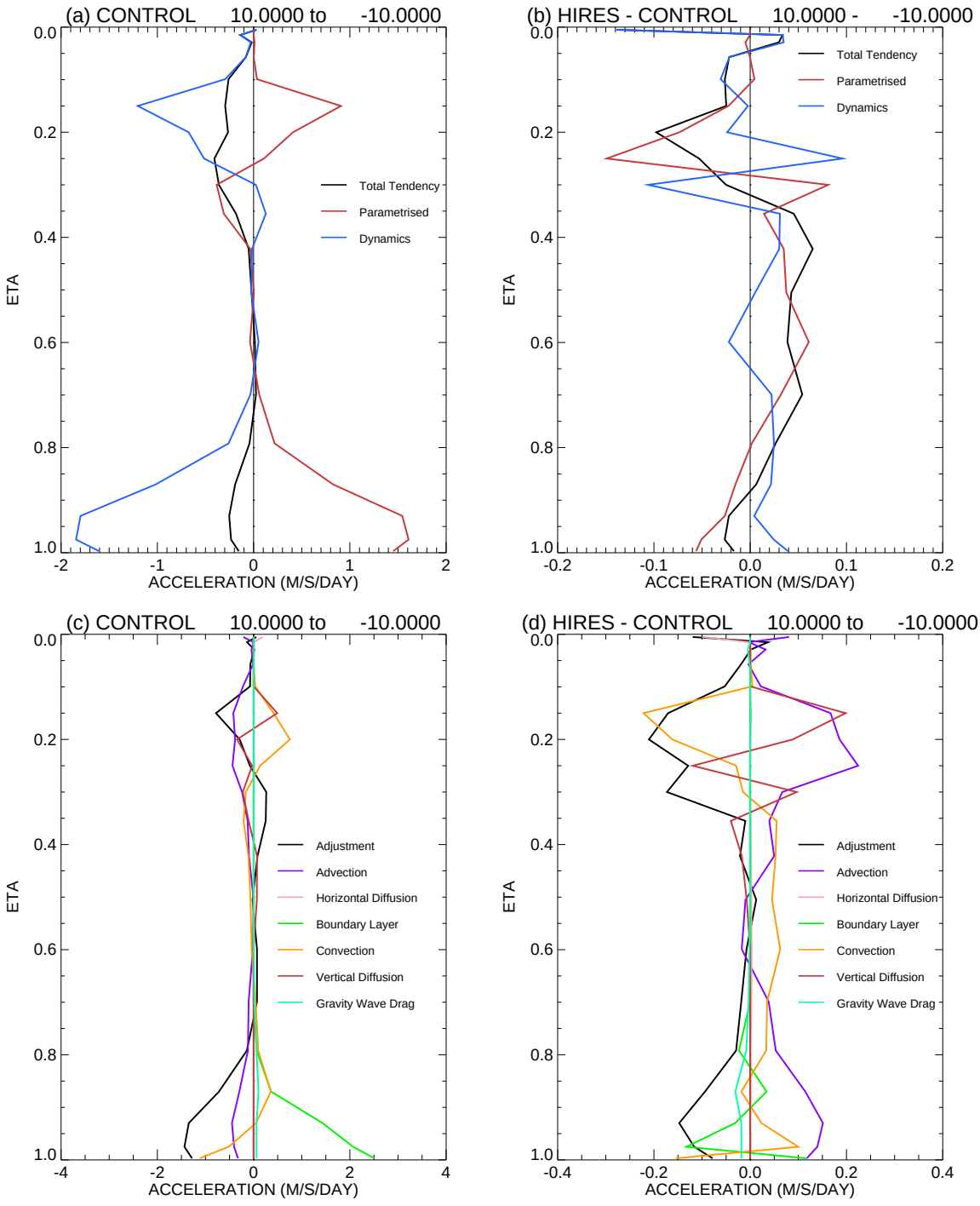

Figure 9: As figure 8, but for the tropical latitude band 10N to 10S.

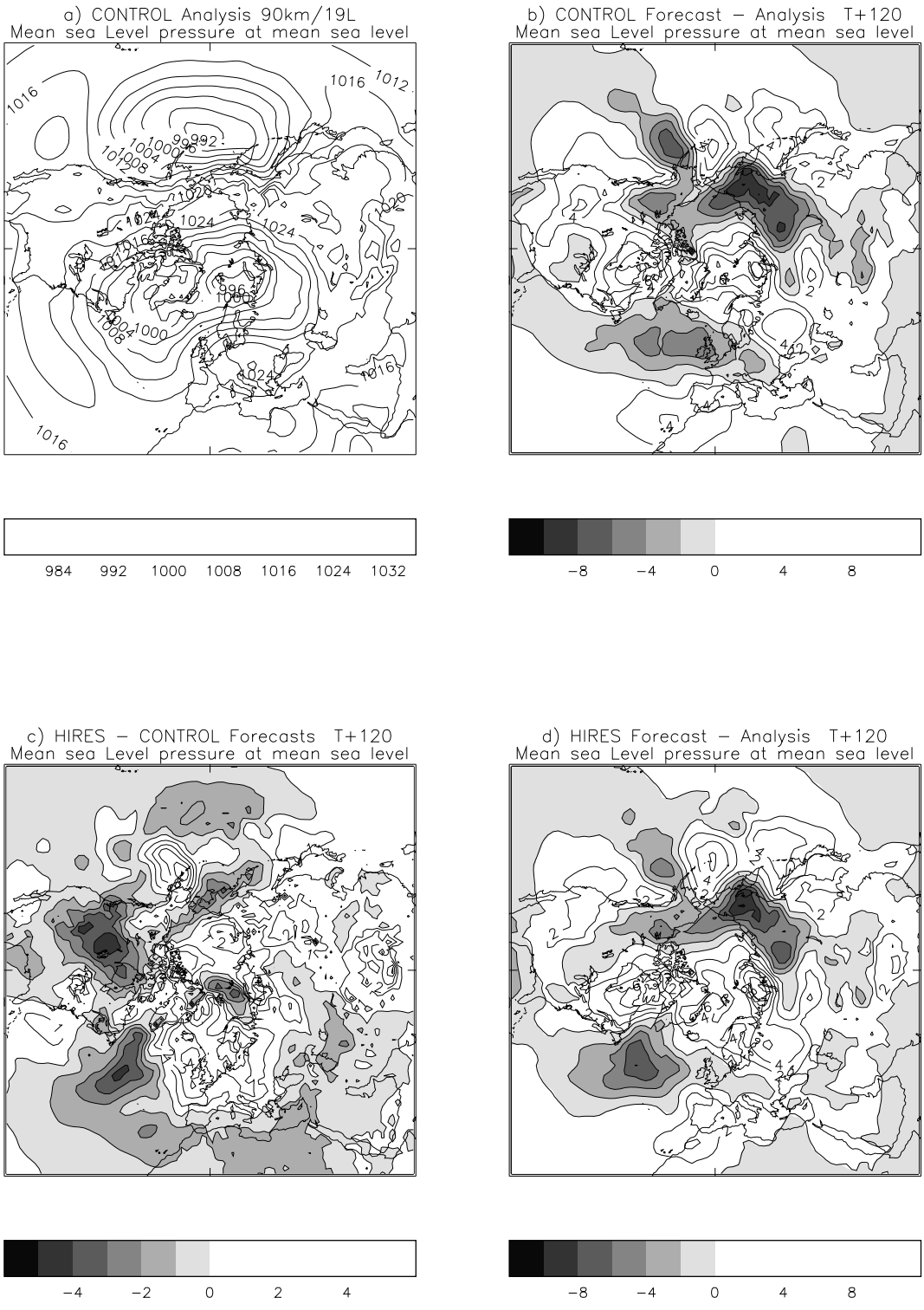

Figure 10: Mean sea level pressure during January 1997 for a) CONTROL analysis b) CONTROL Forecast - Analysis T+120, c) HIRES - CONTROL Forecasts at T+120 d) HIRES Forecast - Analysis T+120.

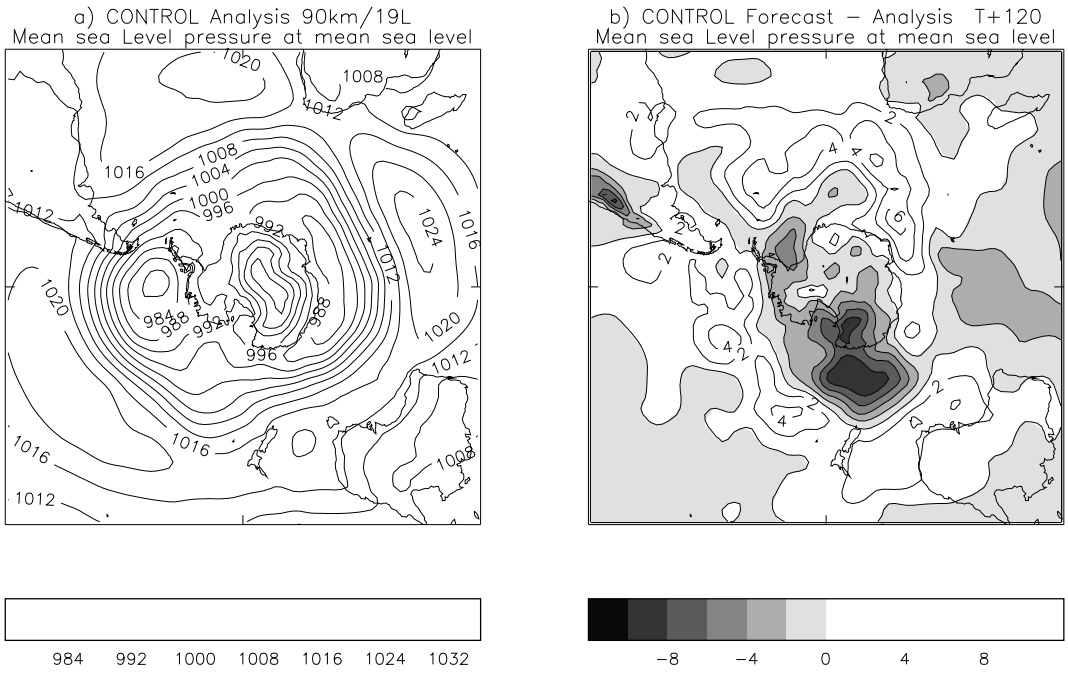

Figure 11: As Figure 10, but for the Southern Hemisphere

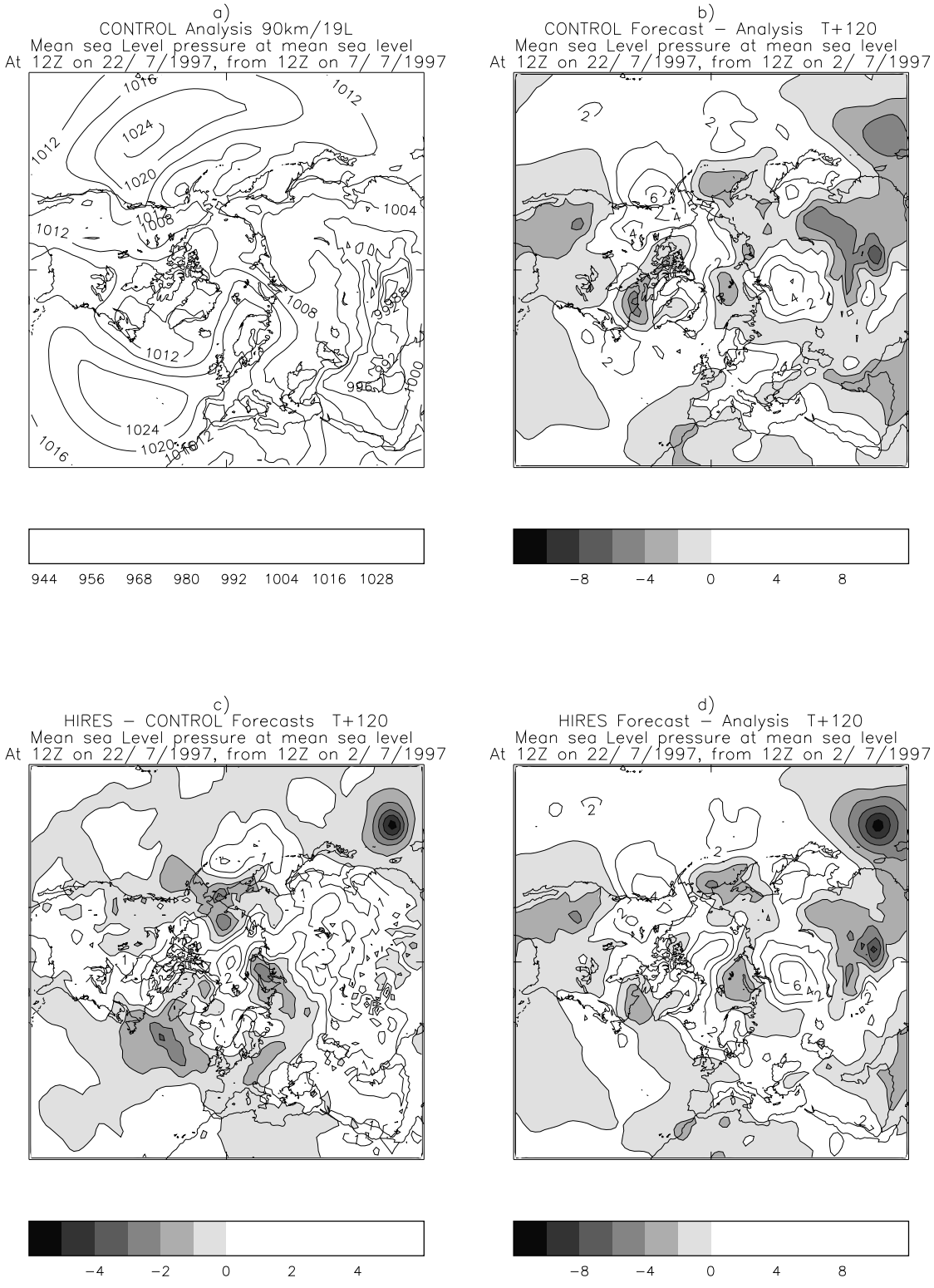

Figure 12: As Figure 10, but for July 1997

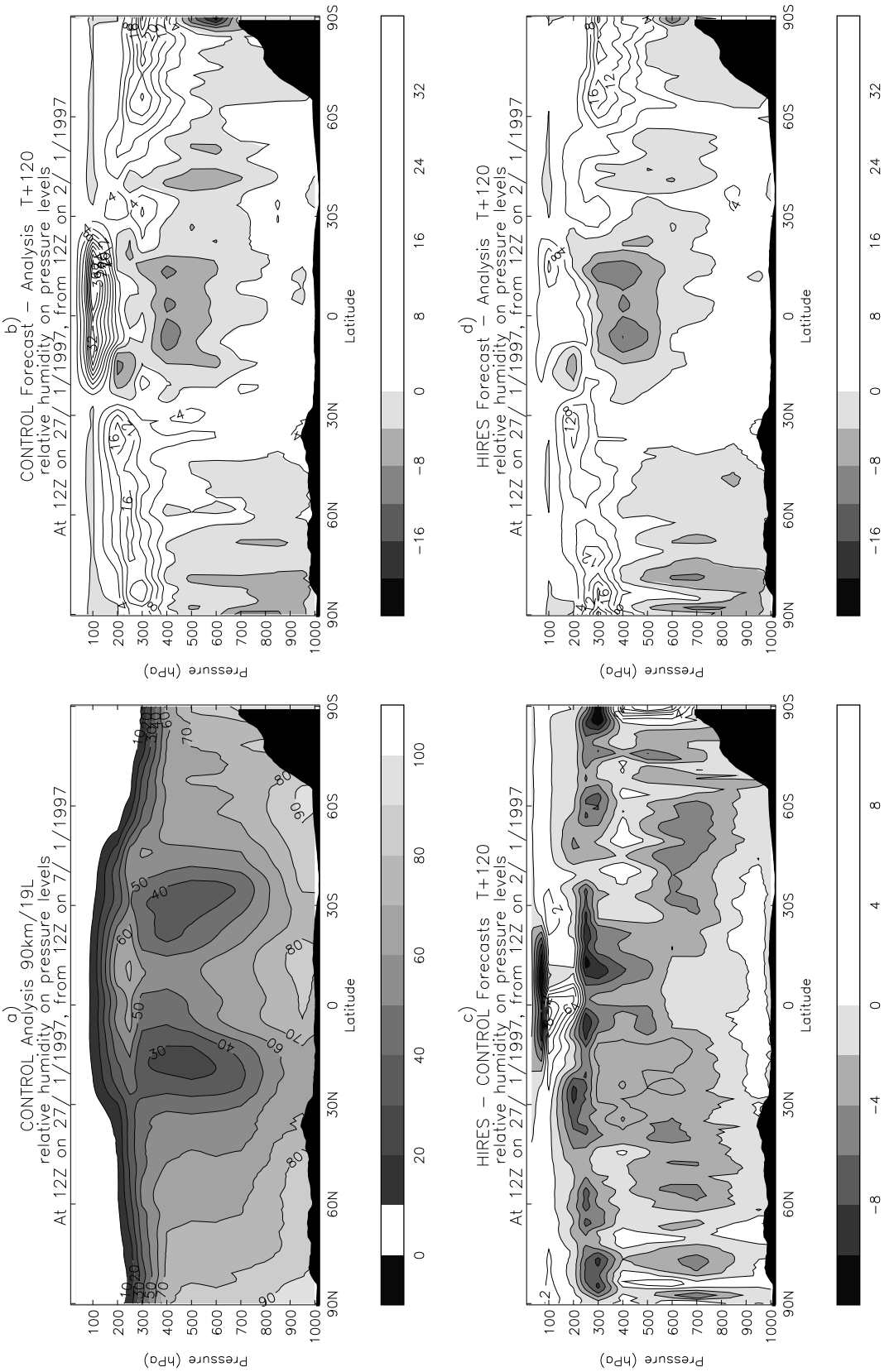

Figure 13: Zonal Average relative humidity during January 1997 for a) CONTROL analysis b) CONTROL Forecast - Analysis T+120, c) HIRES - CONTROL Forecasts at T+120 d) HIRES Forecast - Analysis T+120.

Figure 14: Profiles of zonally averaged specific humidity (shown as logarithm) during January 1997 of CONTROL and HIRES analyses and forecasts for a) Tropical point at 0N b) Extratropical point at 50N. Forecast fields are for T+72. Solid line : CONTROL analysis; Dashed line : CONTROL forecast; Solid line + circles : HIRES analysis; Dashed line + circles : HIRES forecast.

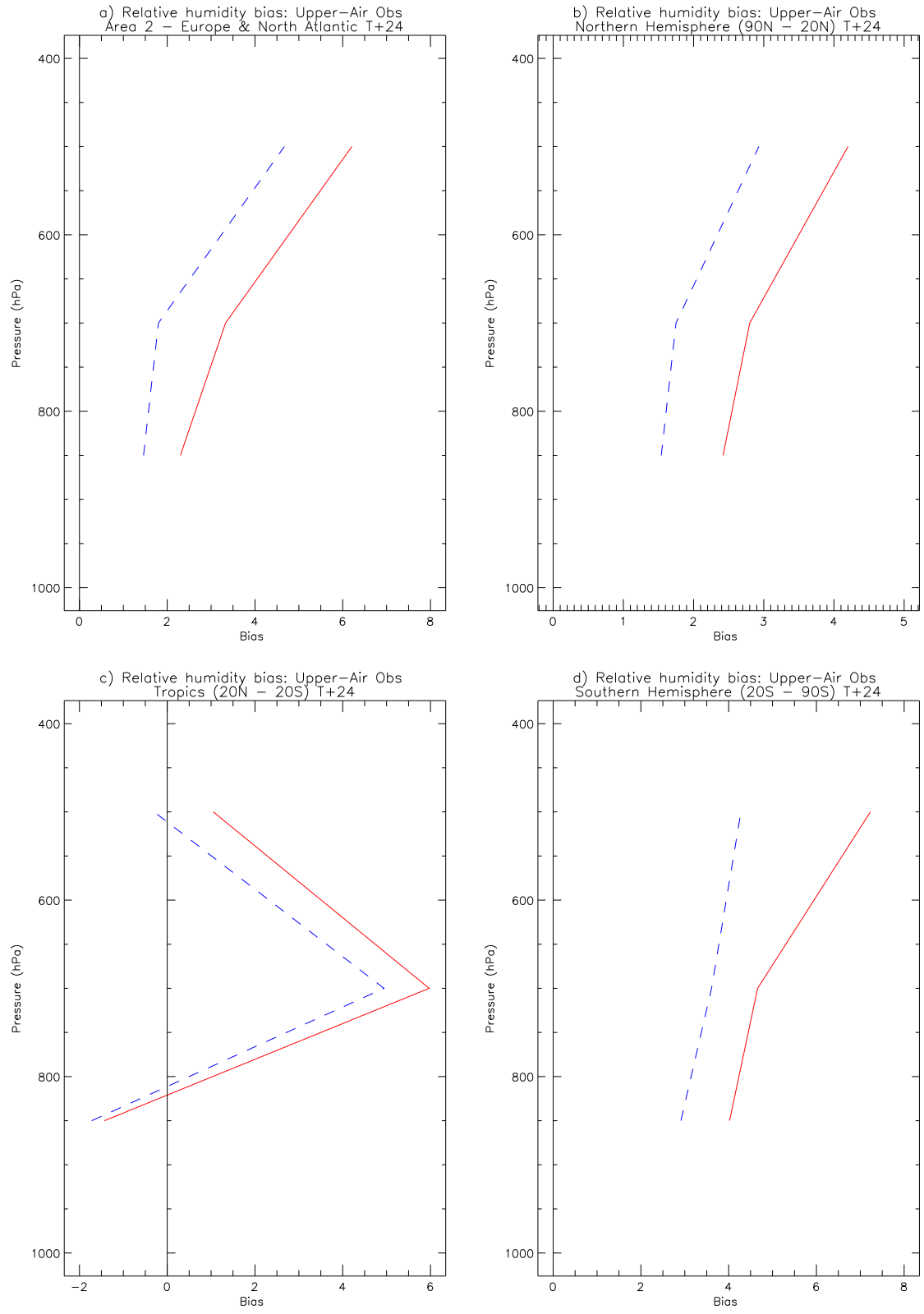

Figure 15: Relative humidity biases verified against radio-sondes at T+24 for January 1997. The solid line is the CONTROL and the dashed line is the HIRES model. (a) Europe & North Atlantic. (b) NH. (c) Tropics. (d) SH.

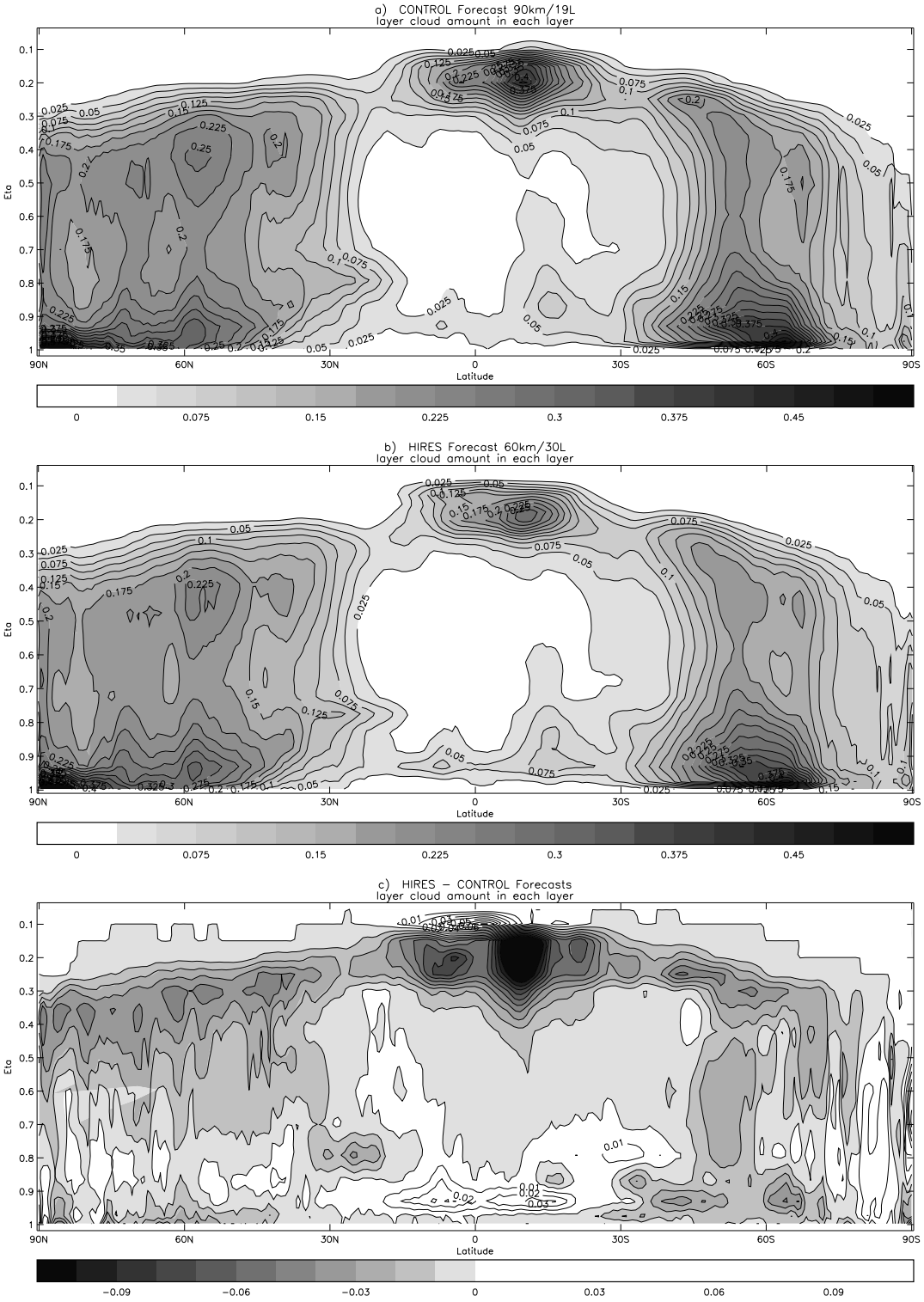

Figure 16: Zonal Average layer cloud during January 1997 for a) CONTROL analysis b) HIRES Forecast - Analysis, c) HIRES - CONTROL Forecasts at T+120.

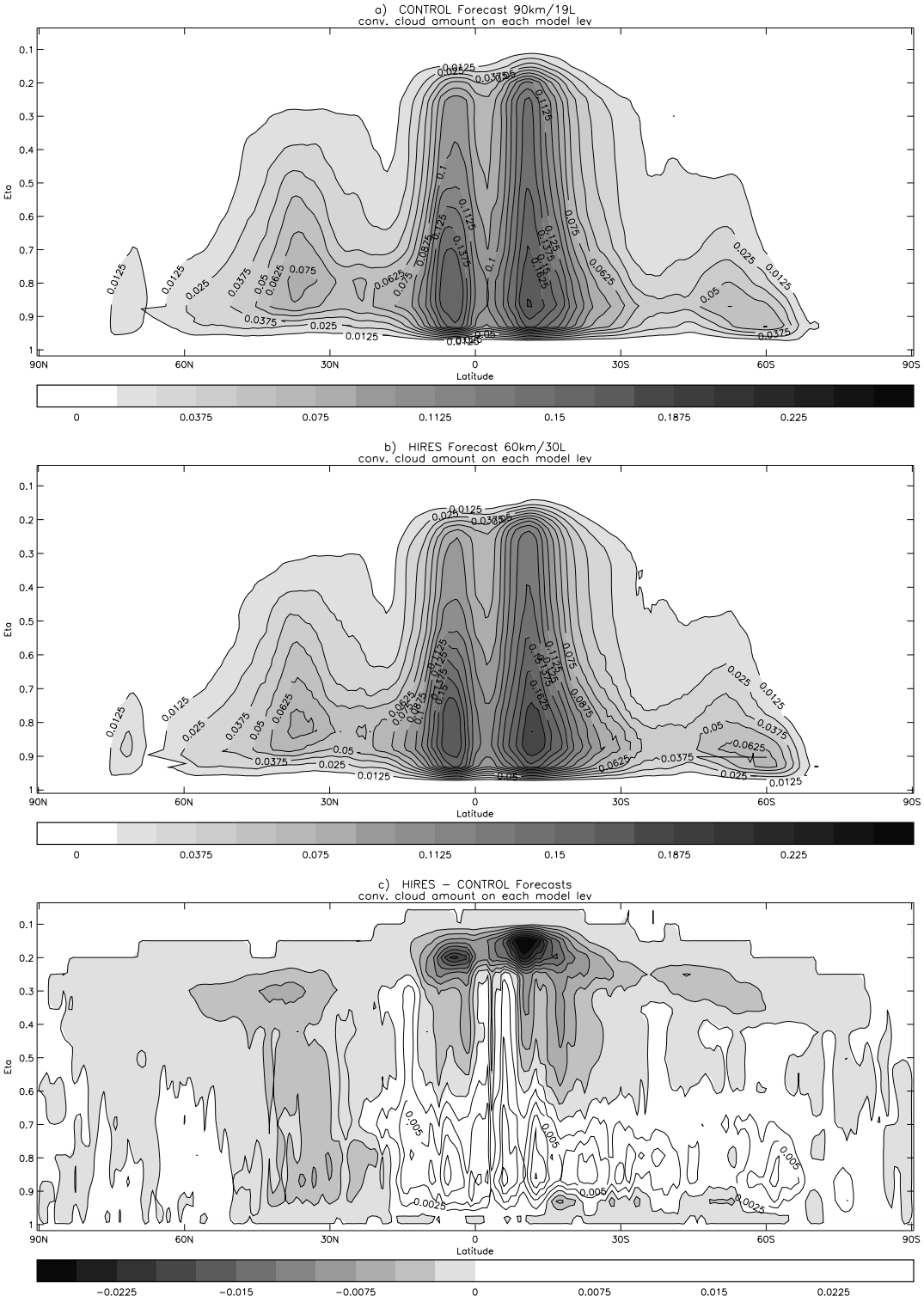

Figure 17: Zonal Average convective cloud during January 1997 for a) CONTROL analysis b) HIRES Forecast - Analysis, c) HIRES - CONTROL Forecasts at T+120.

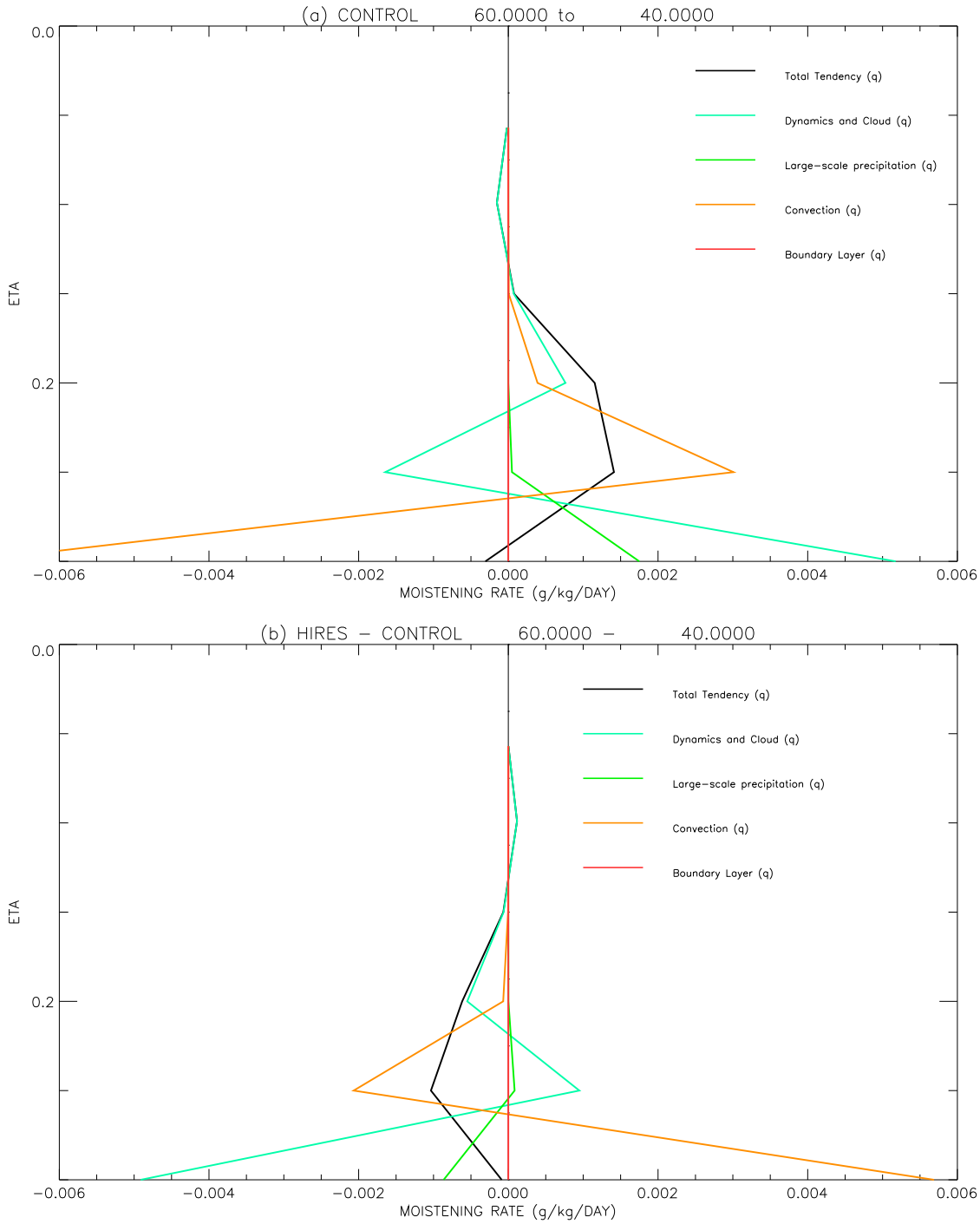

Figure 18: Average moisture budget for 60N to 40N meaned over the first 24 hours of the January trial forecasts. (a) The control moisture ([q]) budget components. (b) The change in the moisture budget components.

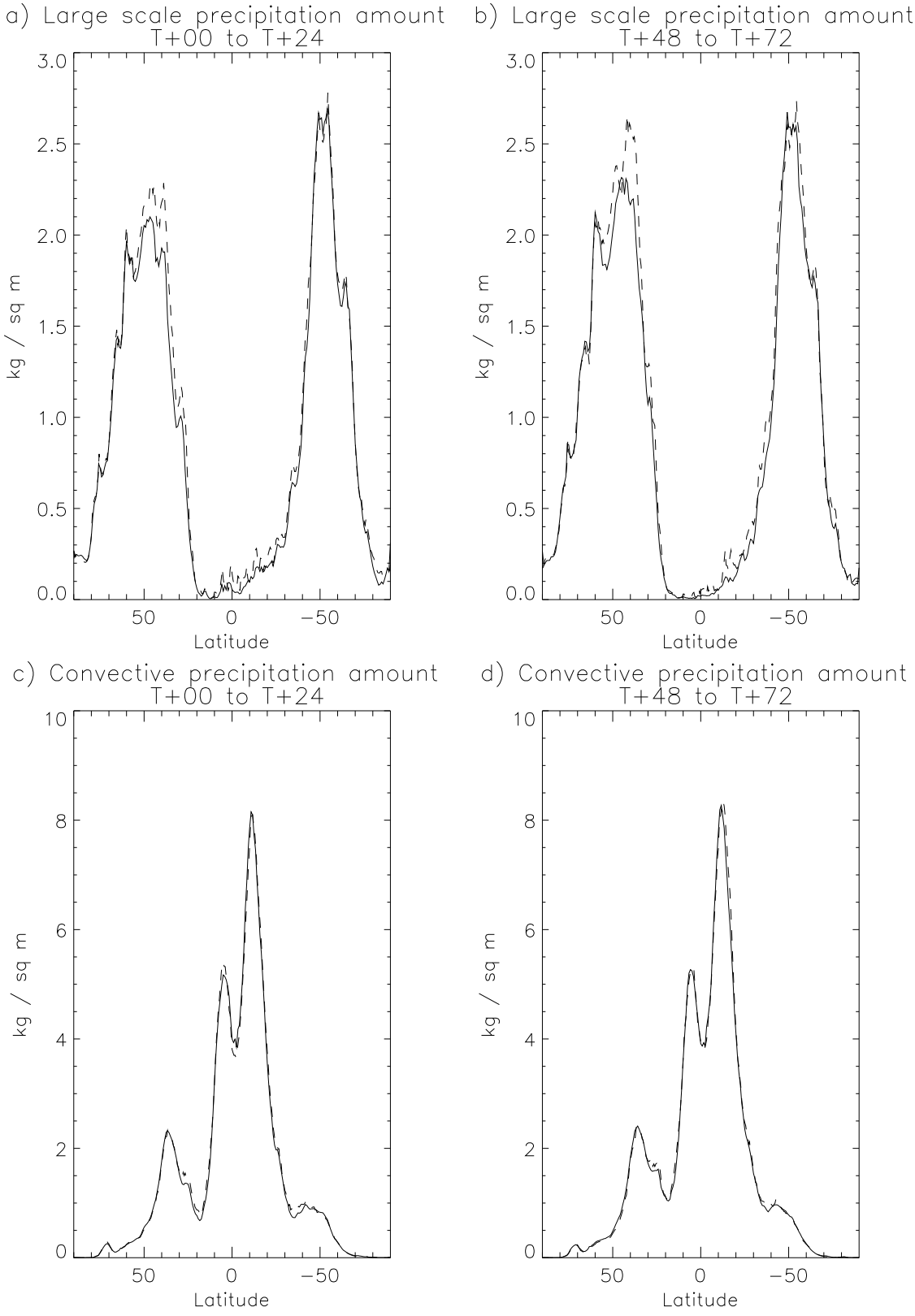

Figure 19: January 1997 zonally averaged 24hr Precipitation accumulations for CONTROL (solid line) and HIRES (dashed line) a) Large scale precipitation T+00-T+24 b) as a) but T+48-T+72, c)Convective precipitation T+00-T+24 d) as c) but T+48-T+72.

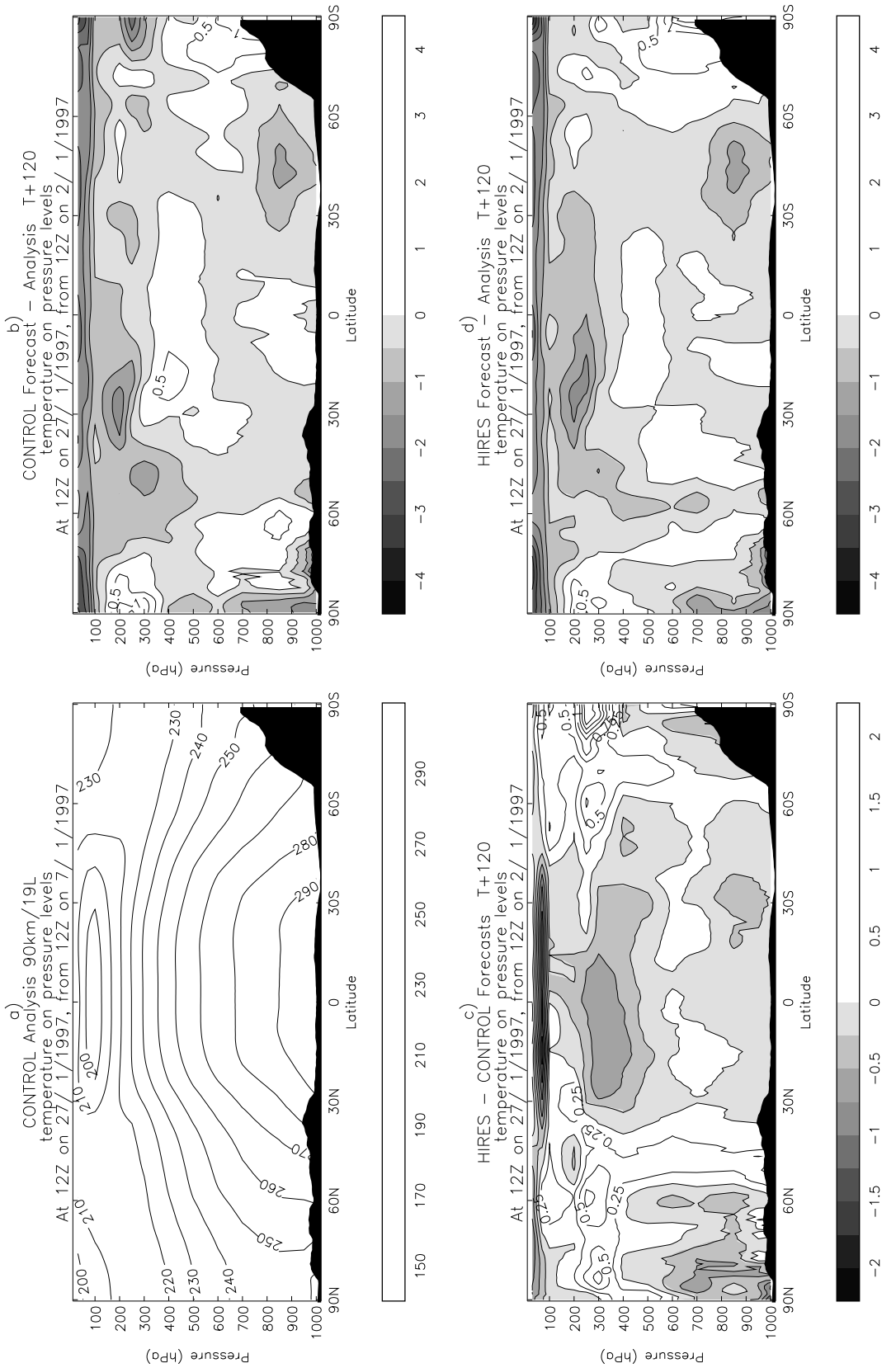

Figure 20: Zonal Average temperature during January 1997 a) CONTROL analysis b) CONTROL Forecast - Analysis T+120, c) HIRES - CONTROL Forecasts at T+120 d) HIRES Forecast - Analysis T+120.

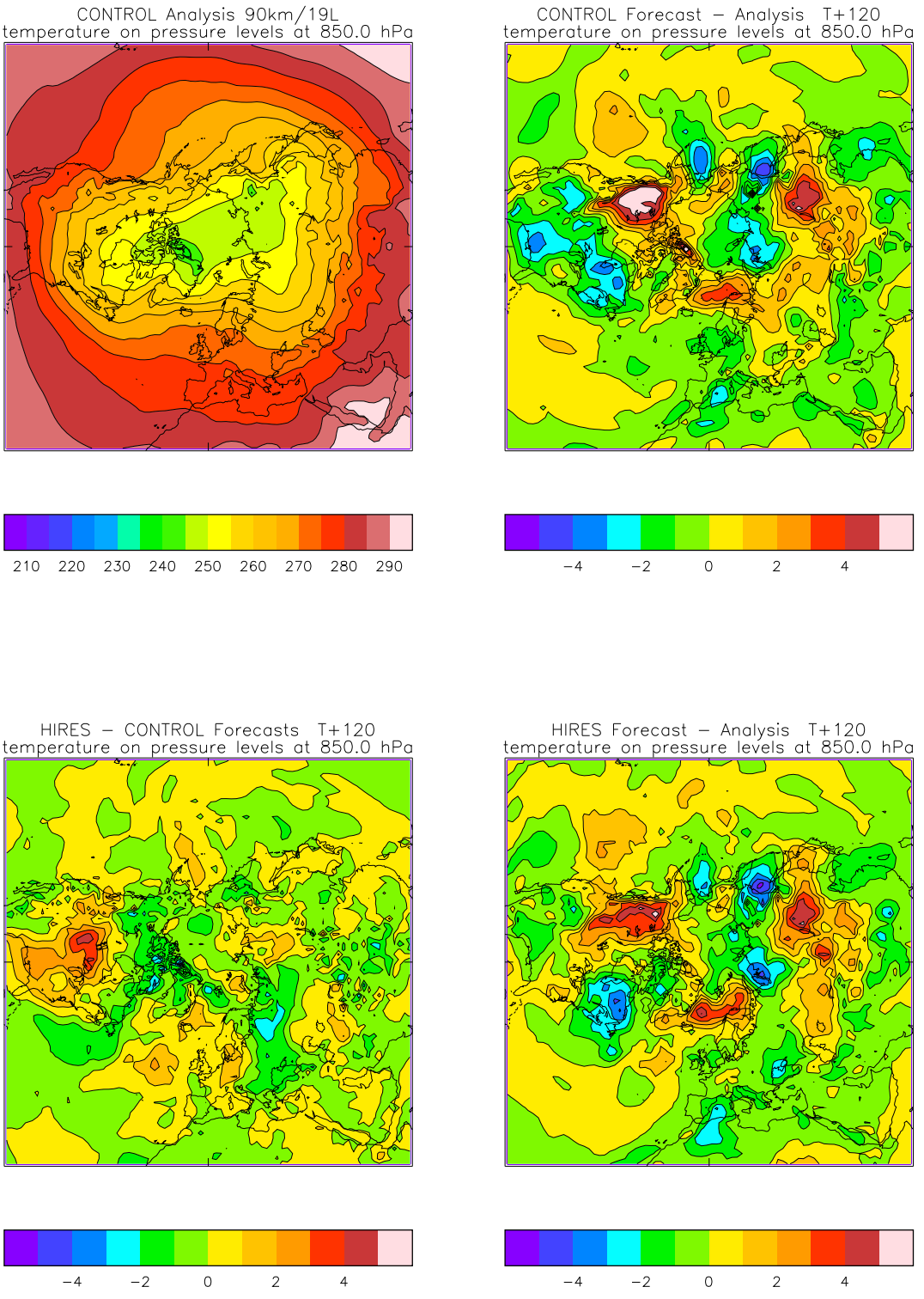

Figure 21: Temperature at 850hPa during January 1997 for a) CONTROL analysis b) CONTROL Forecast - Analysis T+120, c) HIRES - CONTROL Forecasts at T+120 d) HIRES Forecast - Analysis T+120.

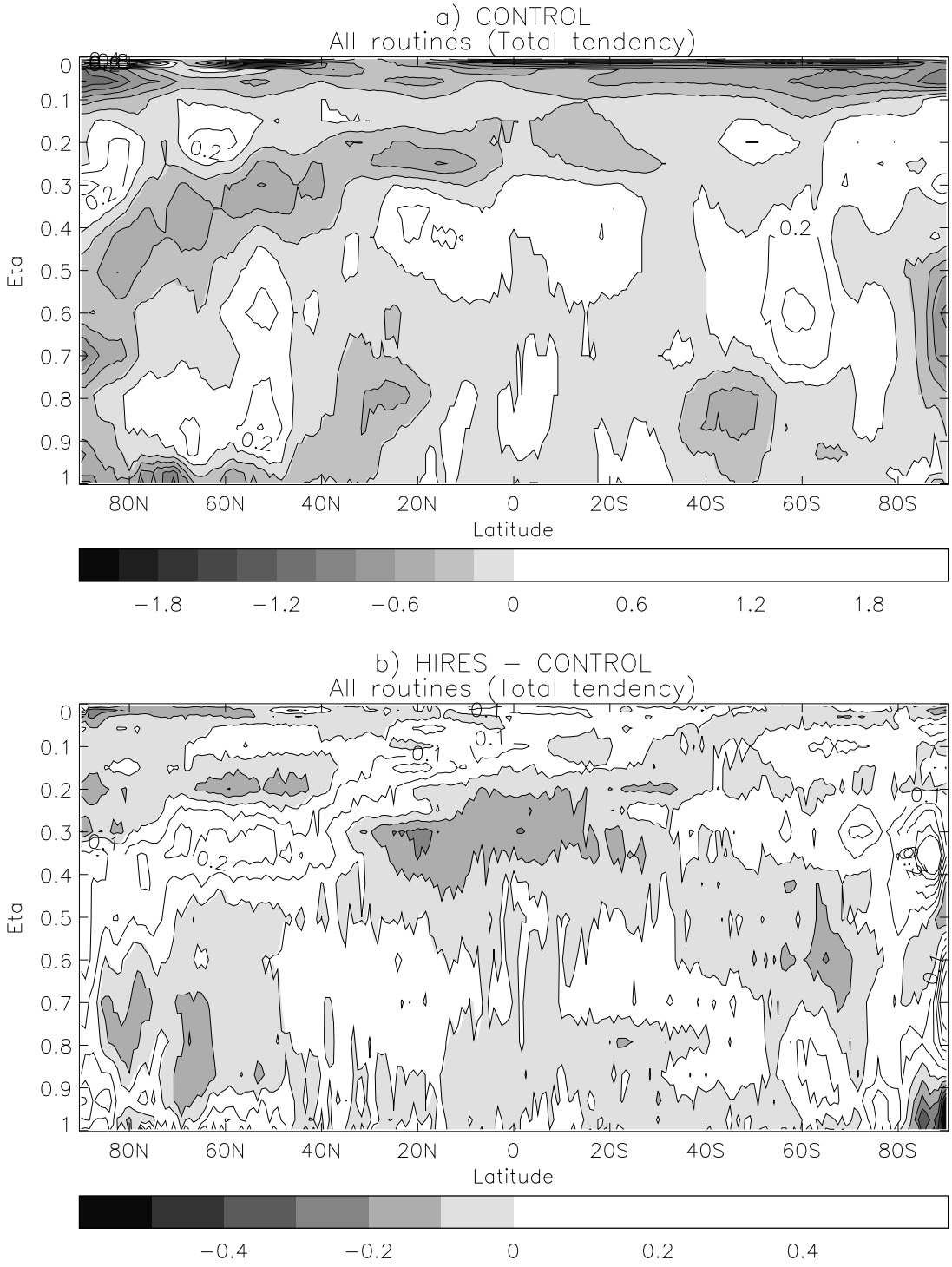

Figure 22: Thermal balance for T+00 to T+24 in the Unified Model for HIRES vs CONTROL during January 1997. a) Total (residual) tendency (= Parametrizations + Dynamics) .intemperature for CONTROL, b) HIRES - CONTROL difference in the total (residual)tendency in temperature. Heating rates are in K/day. Contour interval in a) is 0.2 K/day and in b) is 0.1 K/day.

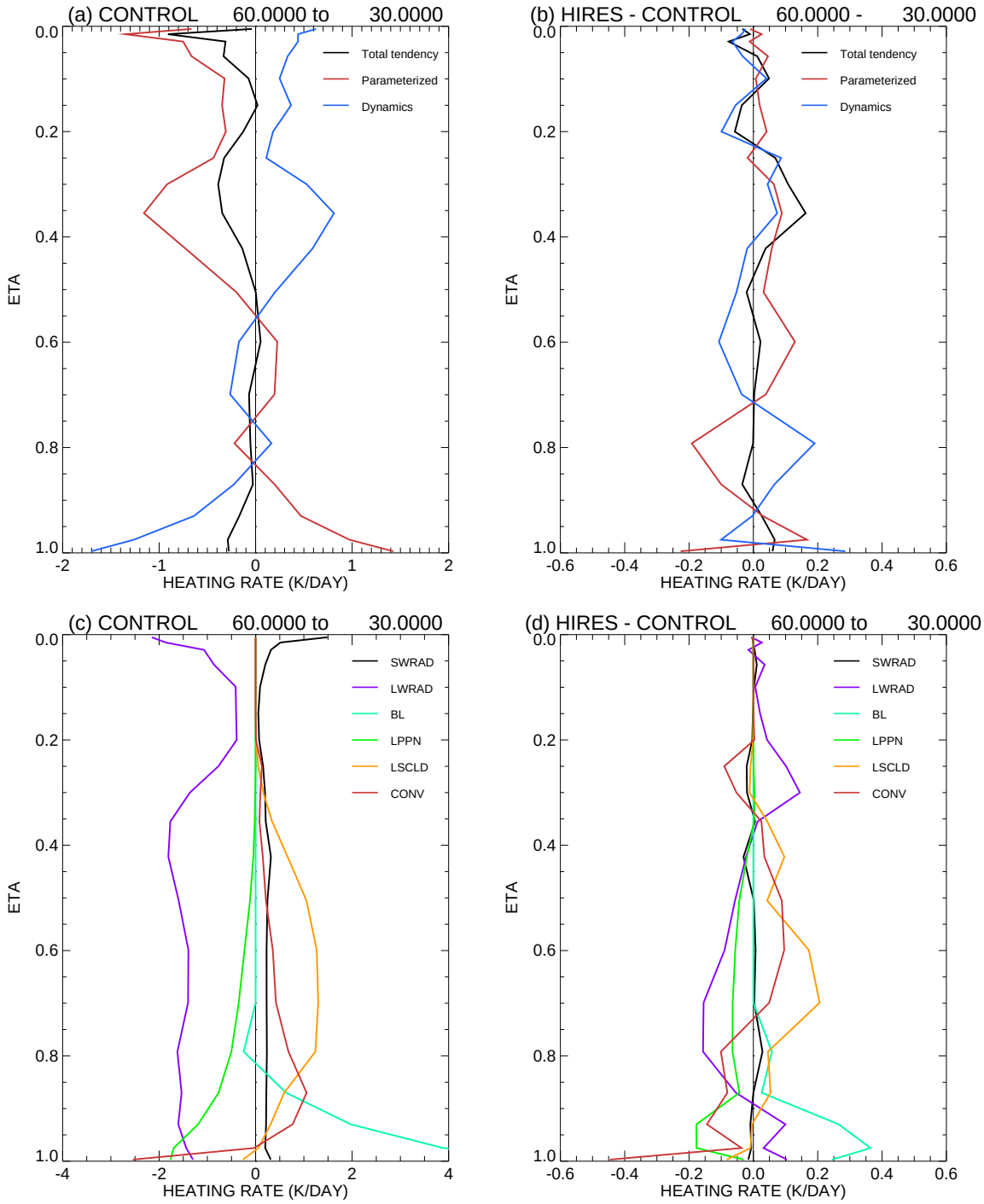

Figure 23: Individual contributions to the zonally averaged thermal balance at T+00 to T+24 for 60N-30N during January 1997. a) CONTROL parametrized, dynamical and total tendency, b)Difference (HIRES - CONTROL) in parametrized, dynamical and total tendency, c)CONTROL parametrized terms, d) Difference (HIRES - CONTROL) in parametrized terms

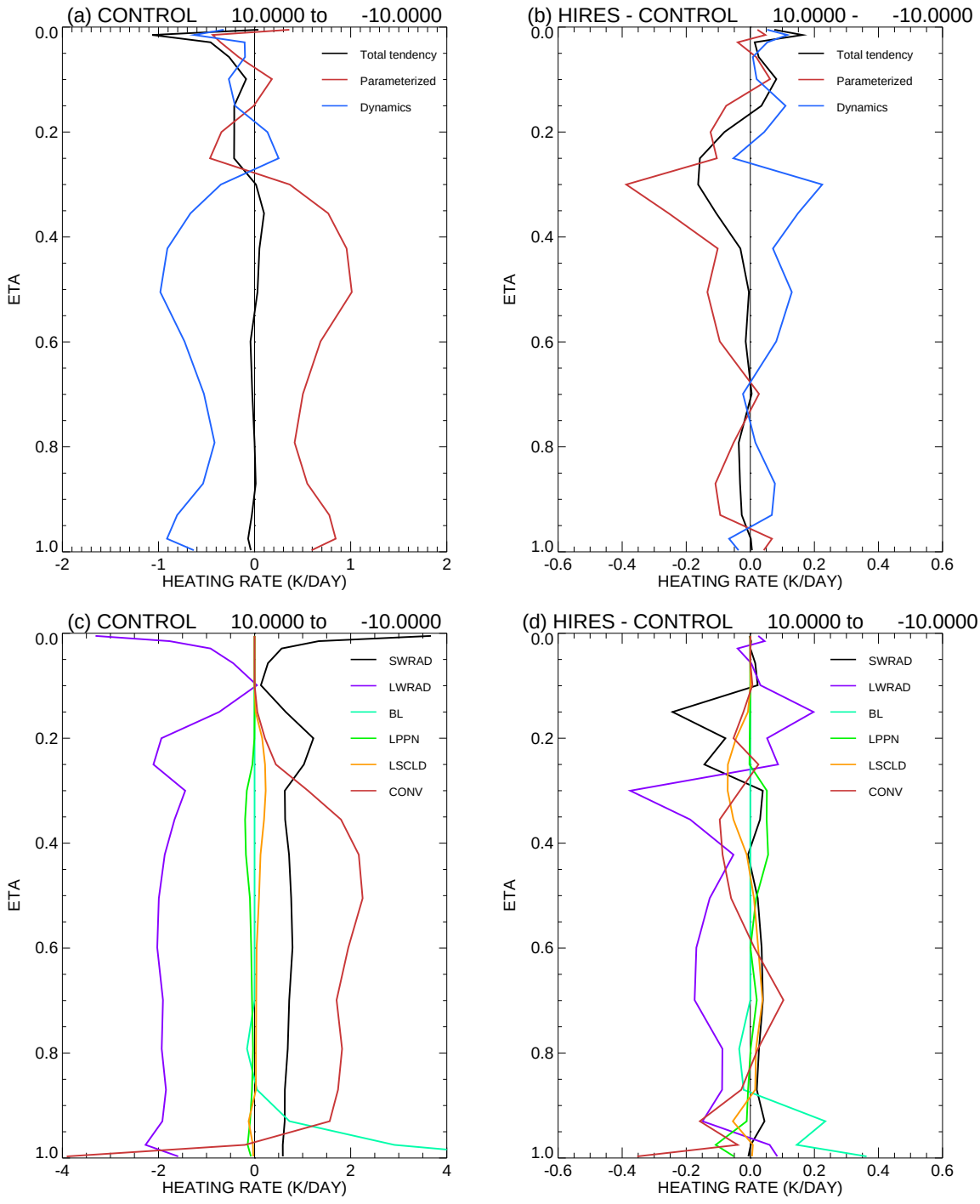

Figure 24: As Fig. 23, but for the Tropical domain 10N-10S

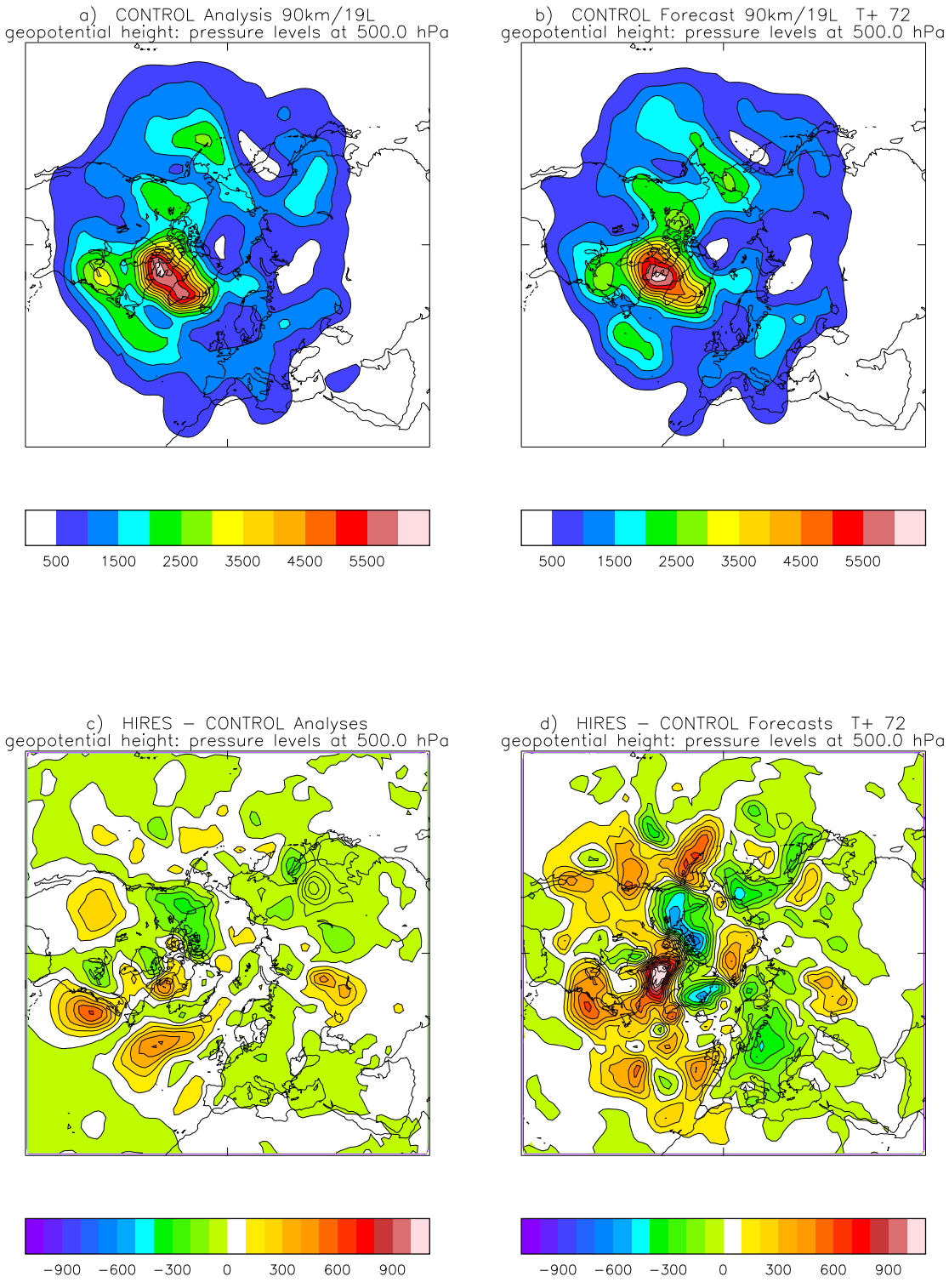

Figure 25: January 1997 variance of the 500hPa geopotential height field for a) CONTROL analysis b) CONTROL Forecast - Analysis T+120, c) HIRES - CONTROL Forecasts at T+120 d) HIRES Forecast - Analysis T+120.

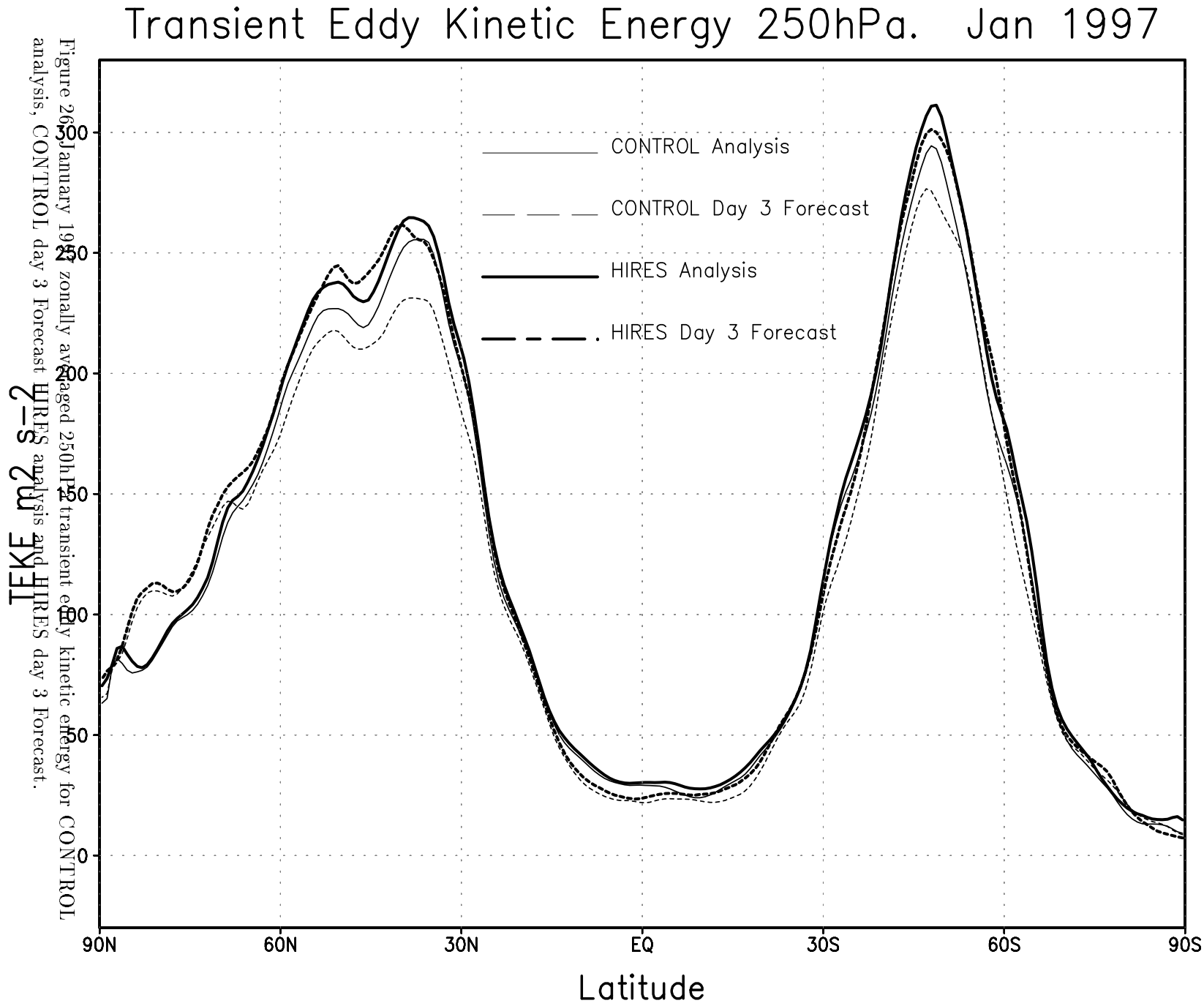

Figure 26: January 1997 zonally averaged 250hPa transient eddy kinetic energy for CONTROL analysis, CONTROL day 3 Forecast HIRES analysis and HIRES day 3 Forecast.

GrADS: COLA/IGES

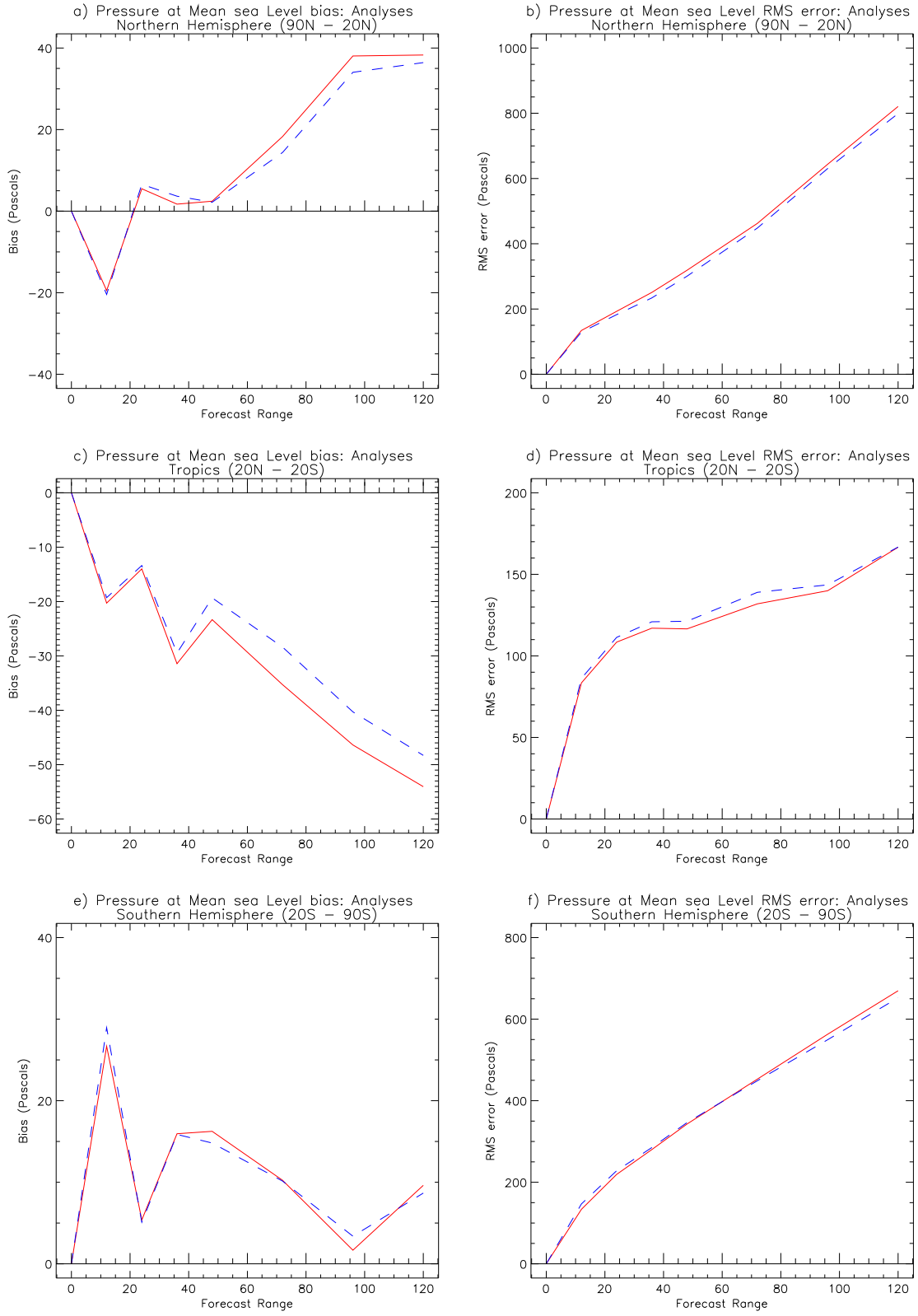

Figure 27: The MSLP biases (left hand column) and RMS errors (right hand column) against analyses as a function of forecast range for January 1997. The solid line is the CONTROL and the dashed line is the HIRES model. (a) Bias in NH. (b) RMS in error NH. (c) Bias in tropics. (d) RMS error in tropics. (e) Bias in SH. (f) RMS error in SH.

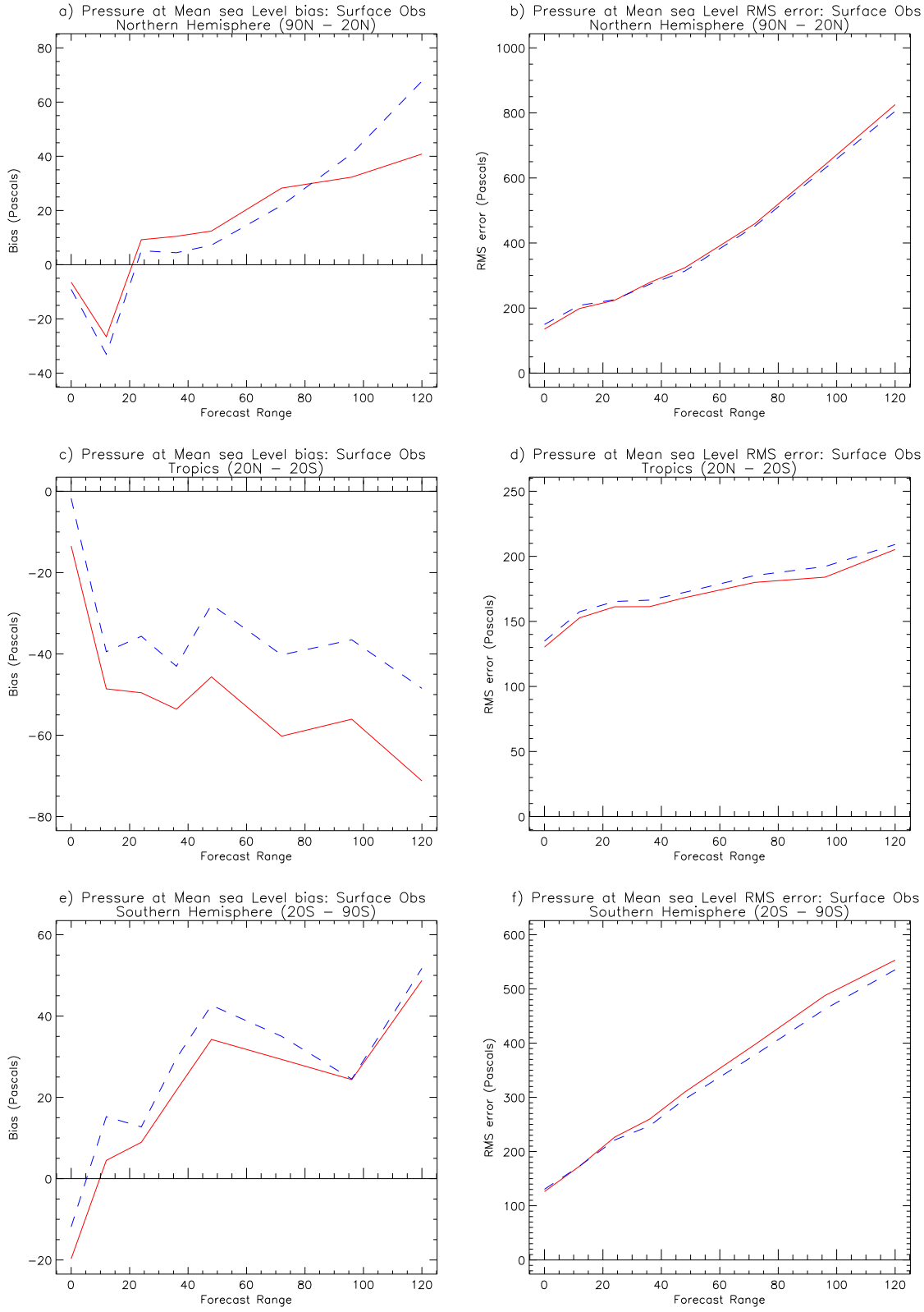

Figure 28: The MSLP biases (left hand column) and RMS errors (right hand column) against SYNOPS as a function of forecast range for January 1997. The solid line is the CONTROL and the dashed line is the HIRES model. (a) Bias in NH. (b) RMS in error NH. (c) Bias in tropics. (d) RMS error in tropics. (e) Bias in SH. (f) RMS error in SH.

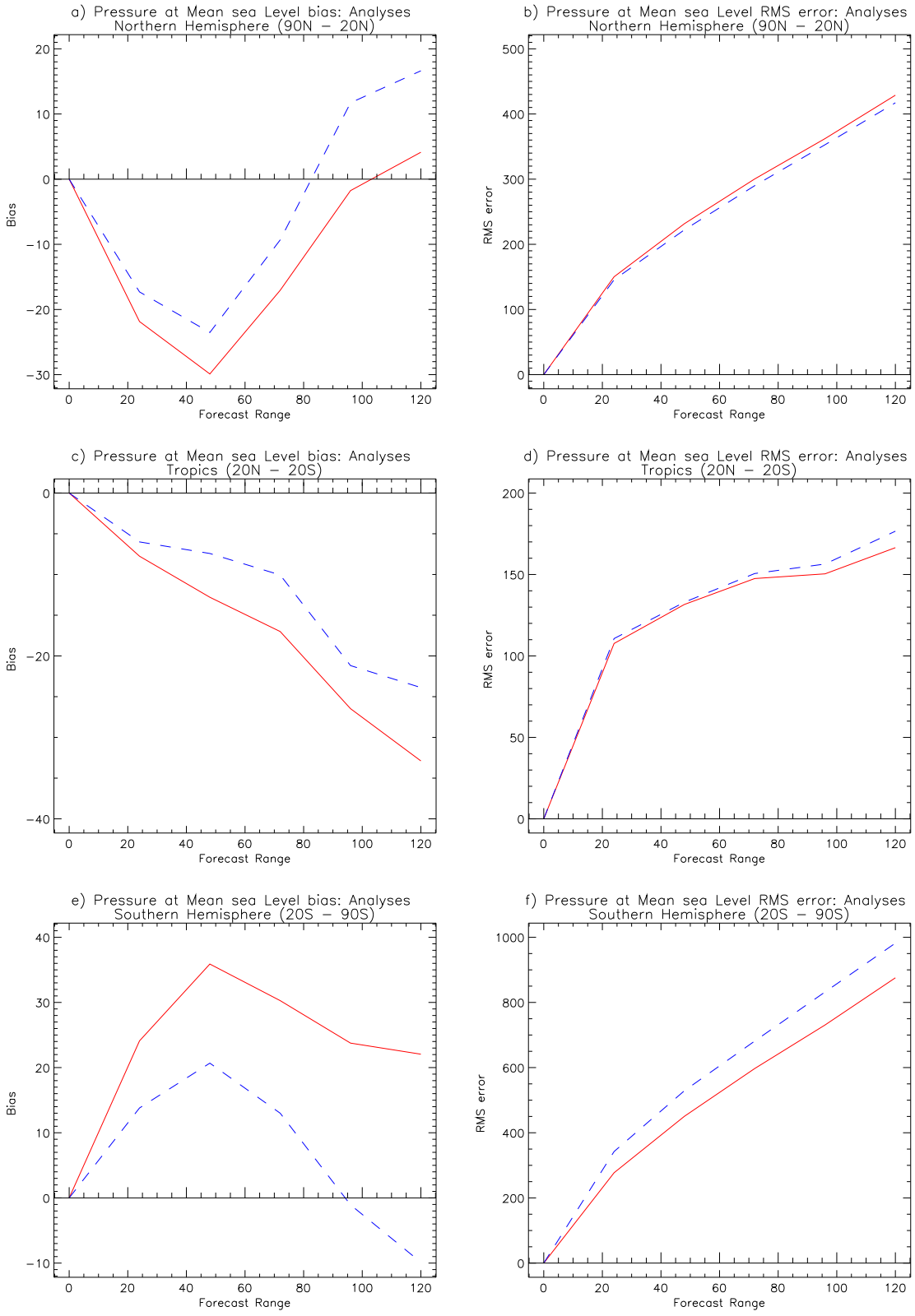

Figure 29: As Figure 27 but for July 1997.

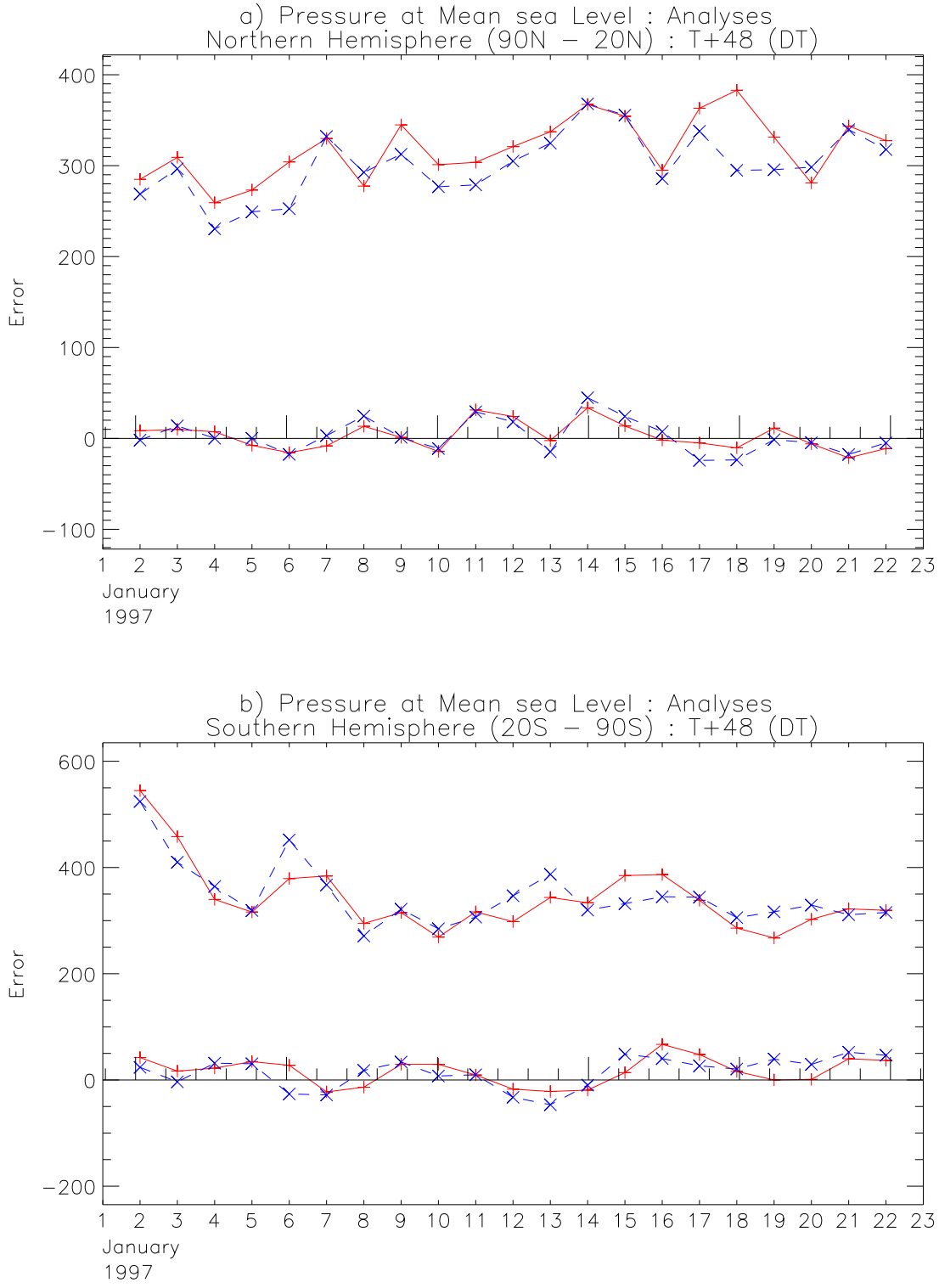

Figure 30: The T+48 MSLP RMS errors for verification of individual forecasts against model analyses during January 1997 trial for (a) Northern Hemisphere, (b) Southern Hemisphere. The solid line is the CONTROL and the dashed line is the HIRES model.

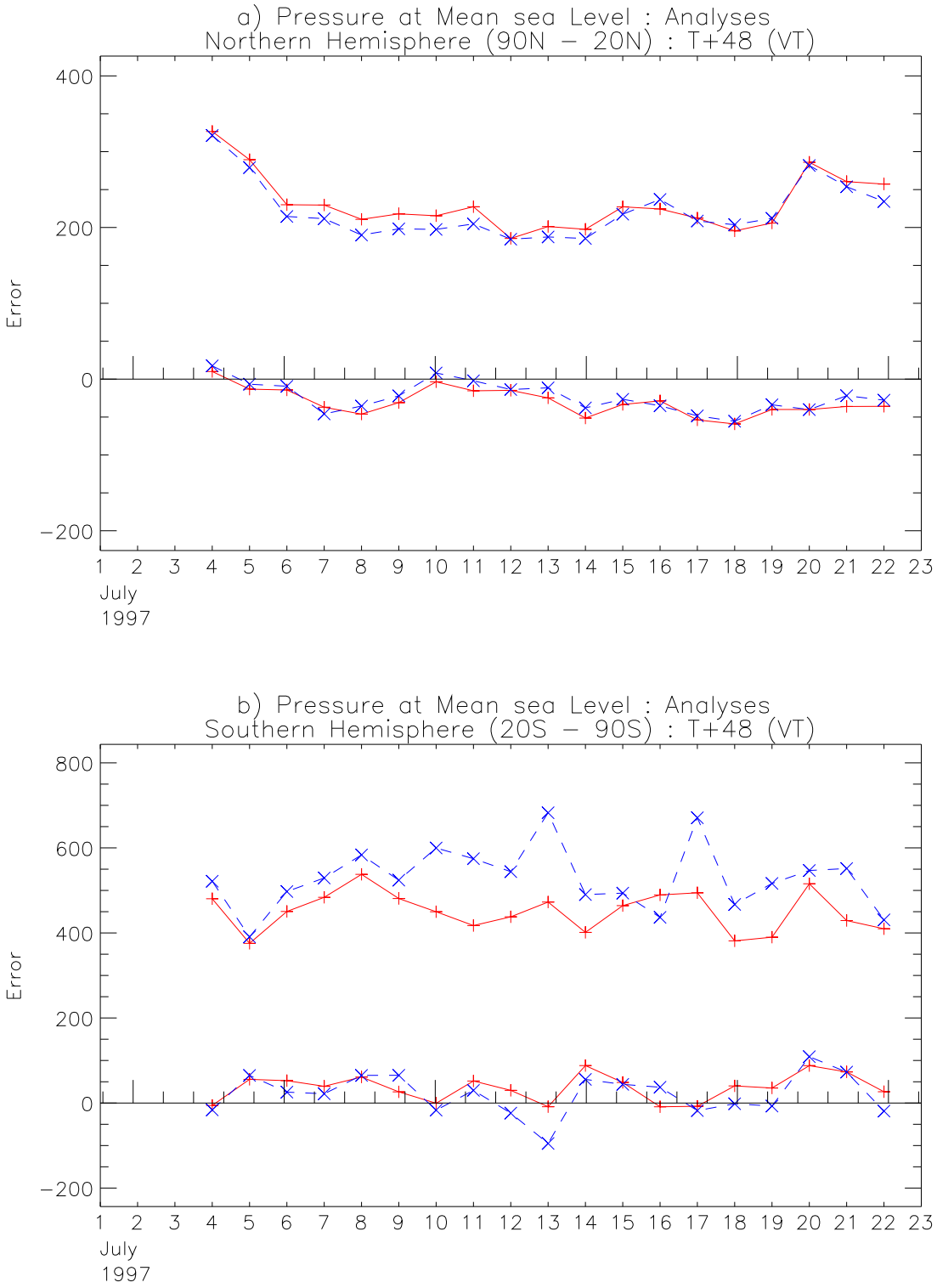

Figure 31: As Figure 30 but for July 1997 trial.

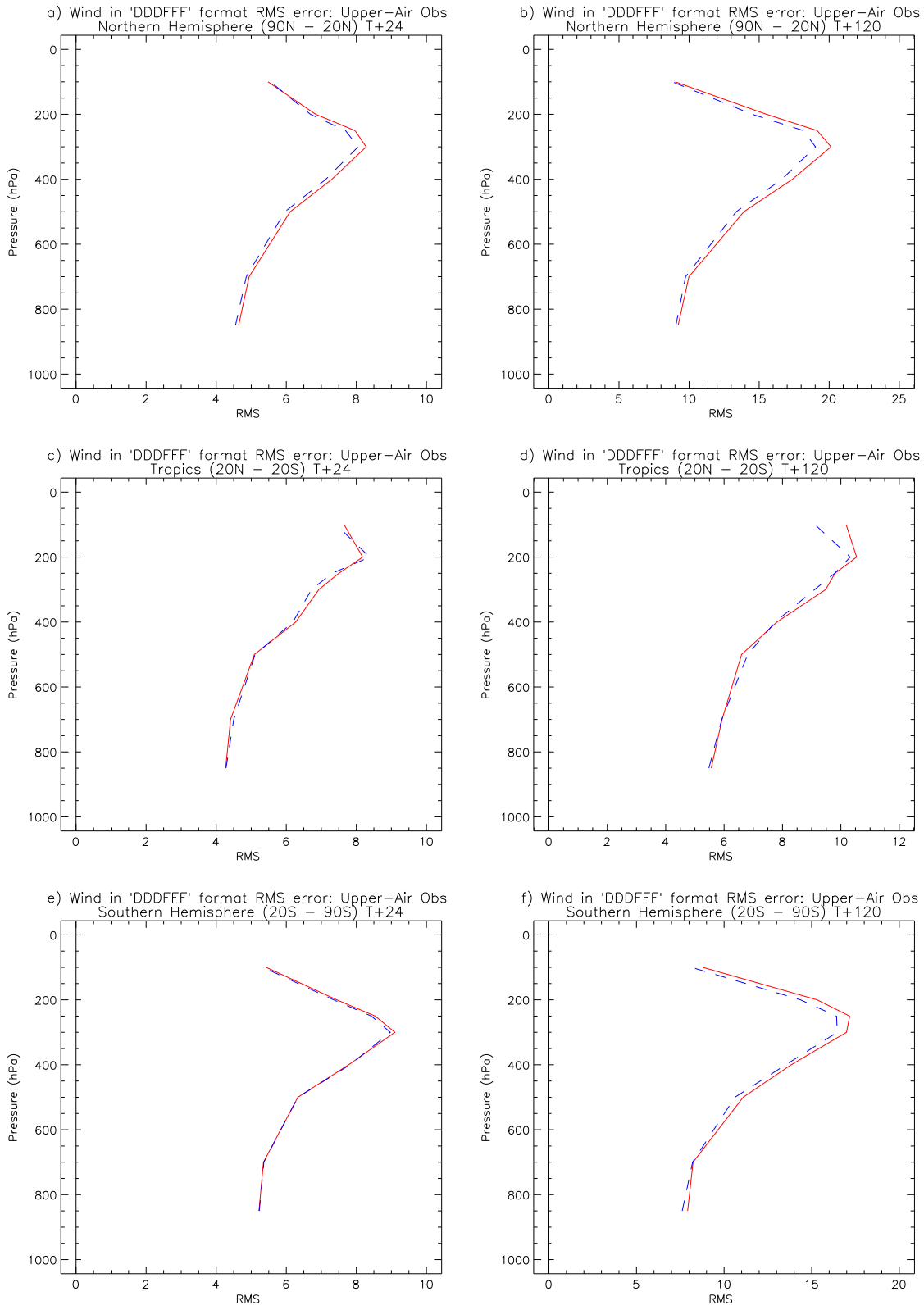

Figure 32: RMS vector wind errors for verification against radiosondes - January 1997. The solid line is the CONTROL and the dashed the HIRES forecasts. (a) NH at T+24. (b) NH at T+120. (c) Tropics at T+24. (d) Tropics at T+120. (e) SH at T+24. (f) SH at T+120.

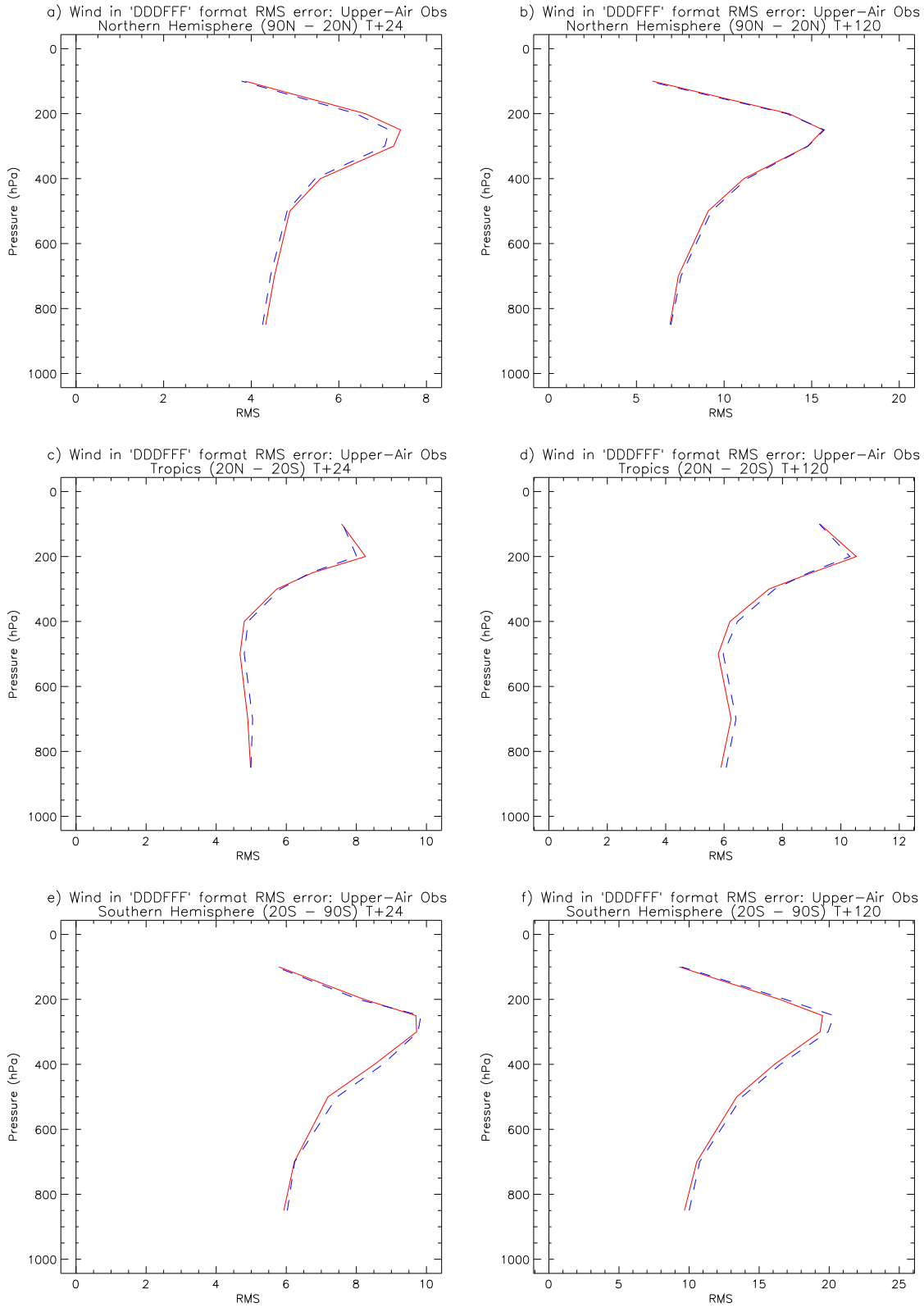

Figure 33: As Figure 32 but for July 1997.

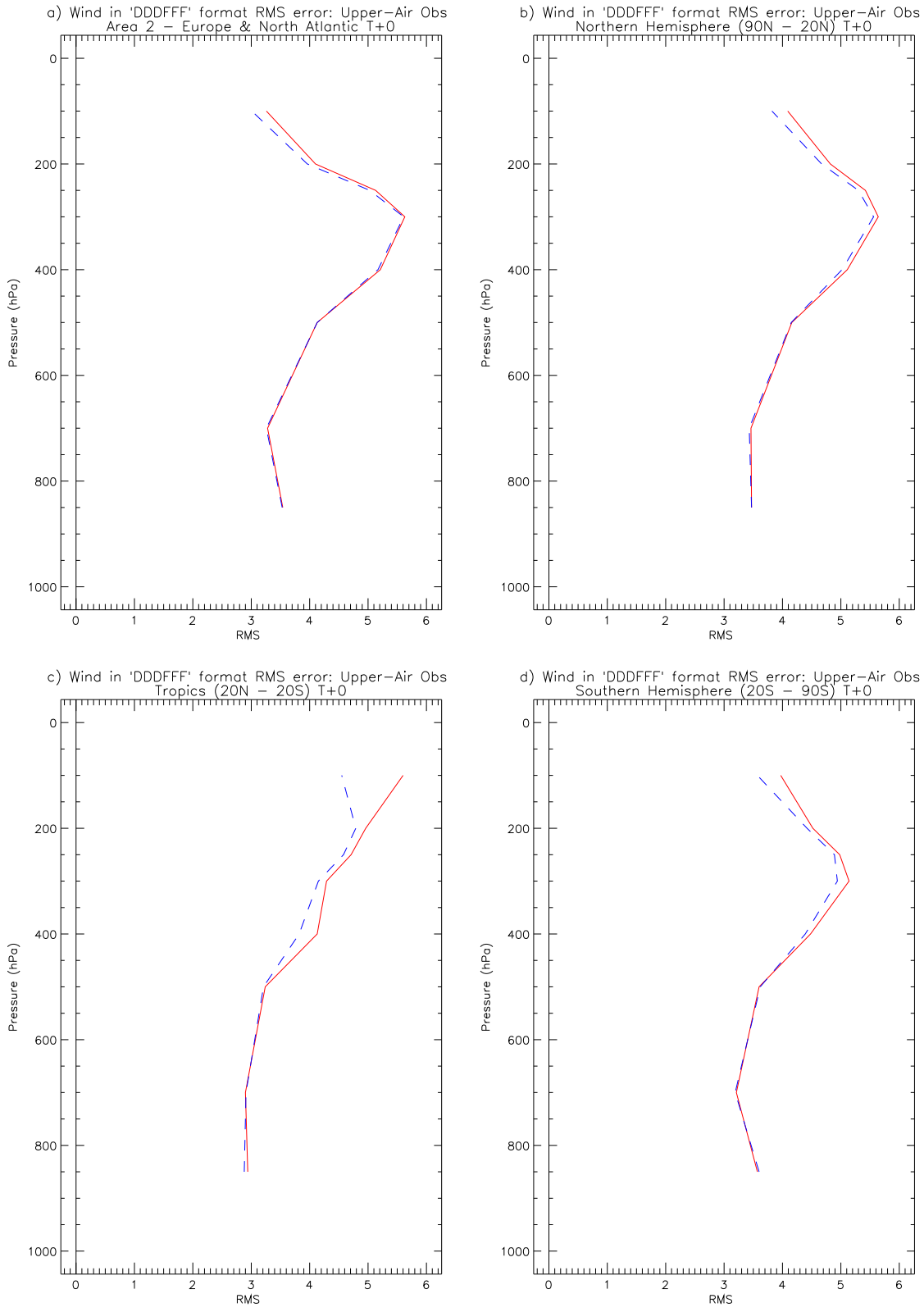

Figure 34: RMS vector wind errors for verification against radio-sondes at T+00. The solid line is the CONTROL and the dashed line is the HIRES model. (a) Europe & North Atlantic. (b) NH. (c) Tropics. (d) SH.

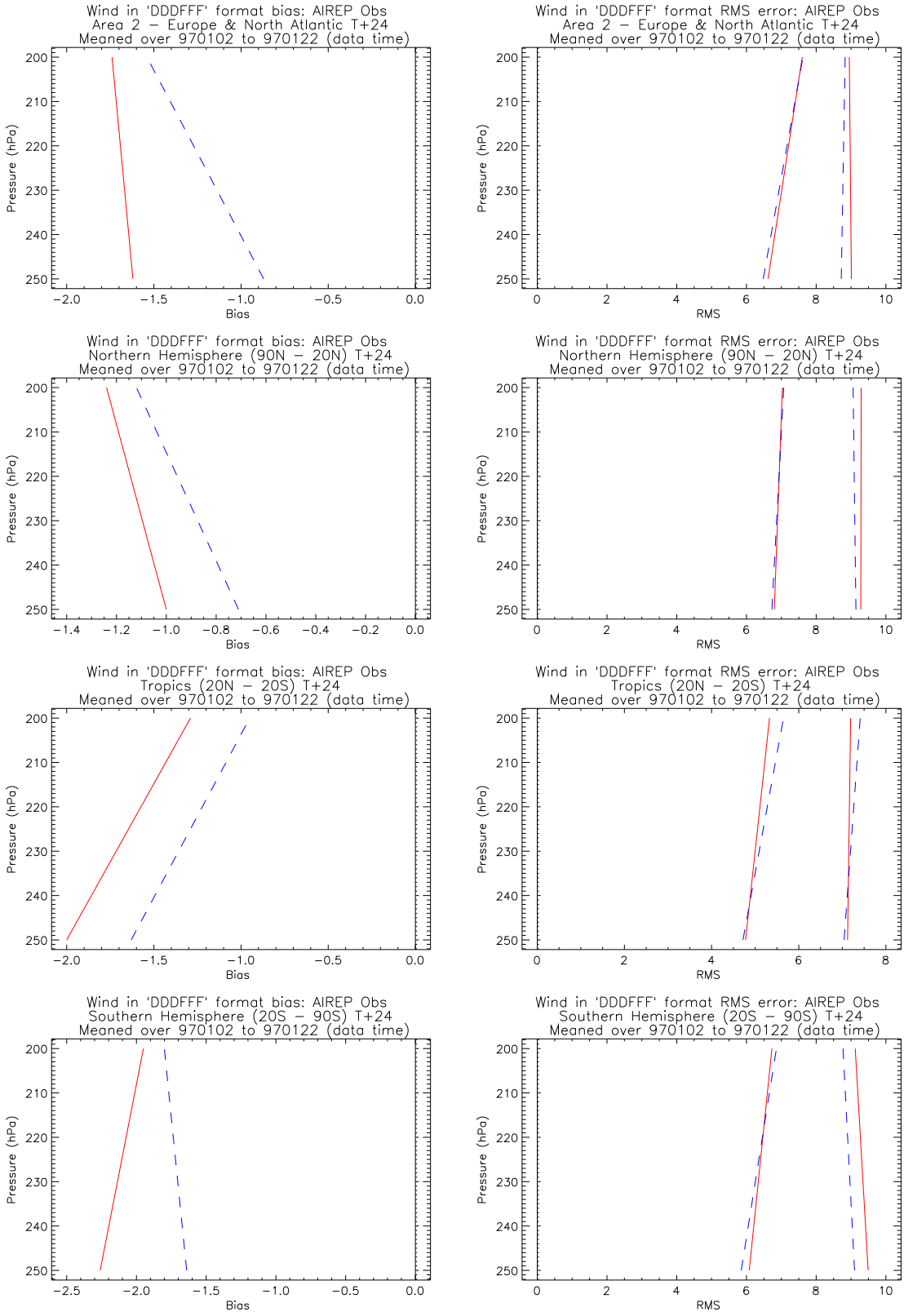

Figure 35: Bias and RMS vector wind errors for verification against AIREP's at T+24. The solid line is the CONTROL and the dashed line is the HIRES model. (a) Europe & North Atlantic. (b) NH. (c) Tropics. (d) SH. (Note: The second set of lines with the smaller values in the RMS vector wind error plots (RH panels) show the fit of the T+00 fields to the AIREP data.)

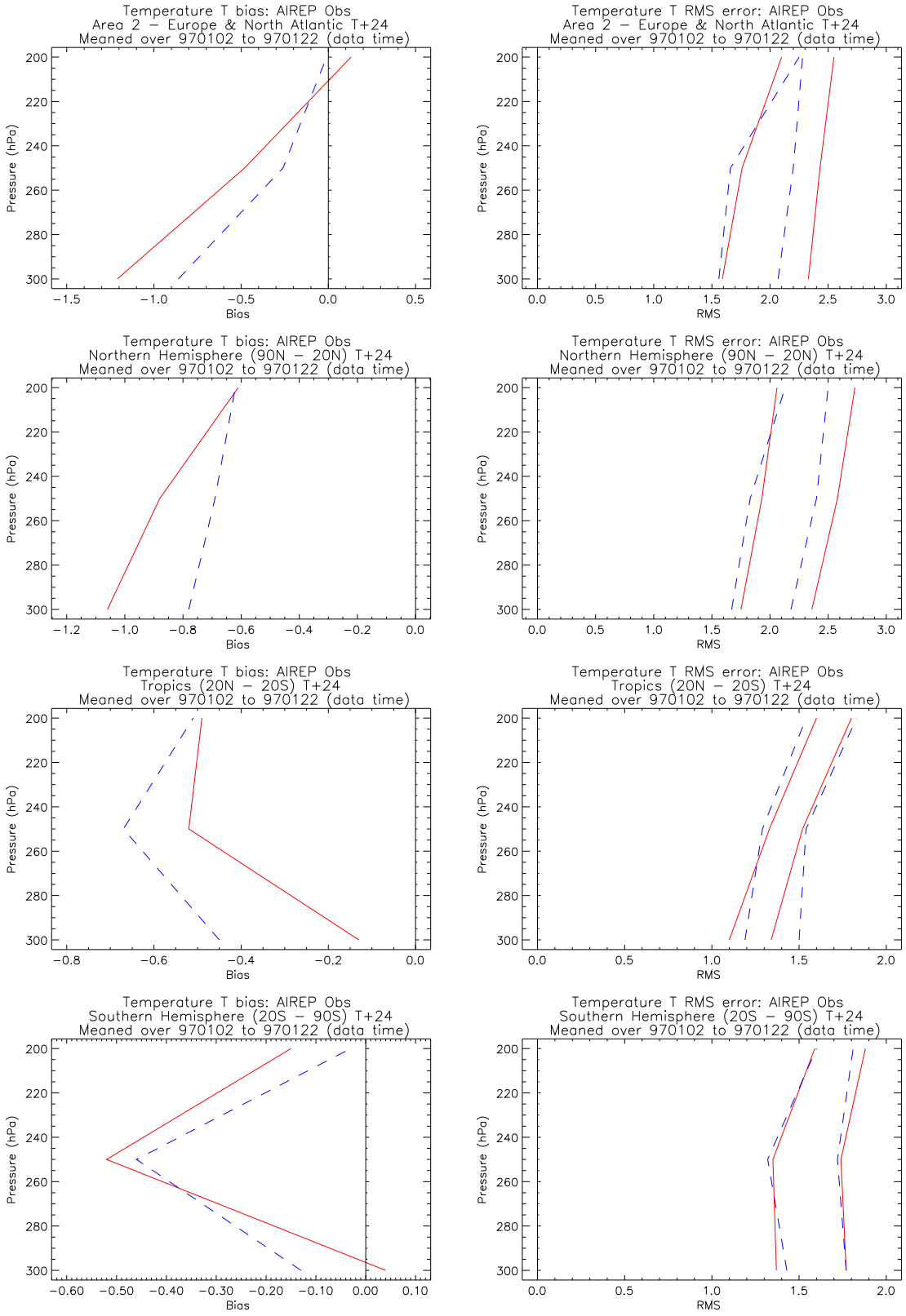

Figure 36: Bias and RMS Temperature errors for verification against AIREP's at T+24. The solid line is the CONTROL and the dashed line is the HIRES model. (a) Europe & North Atlantic. (b) NH. (c) Tropics. (d) SH. (Note: The second set of lines with the smaller values in the RMS error plots (RH panels) show the fit of the T+00 temperature fields to the AIREP data.)

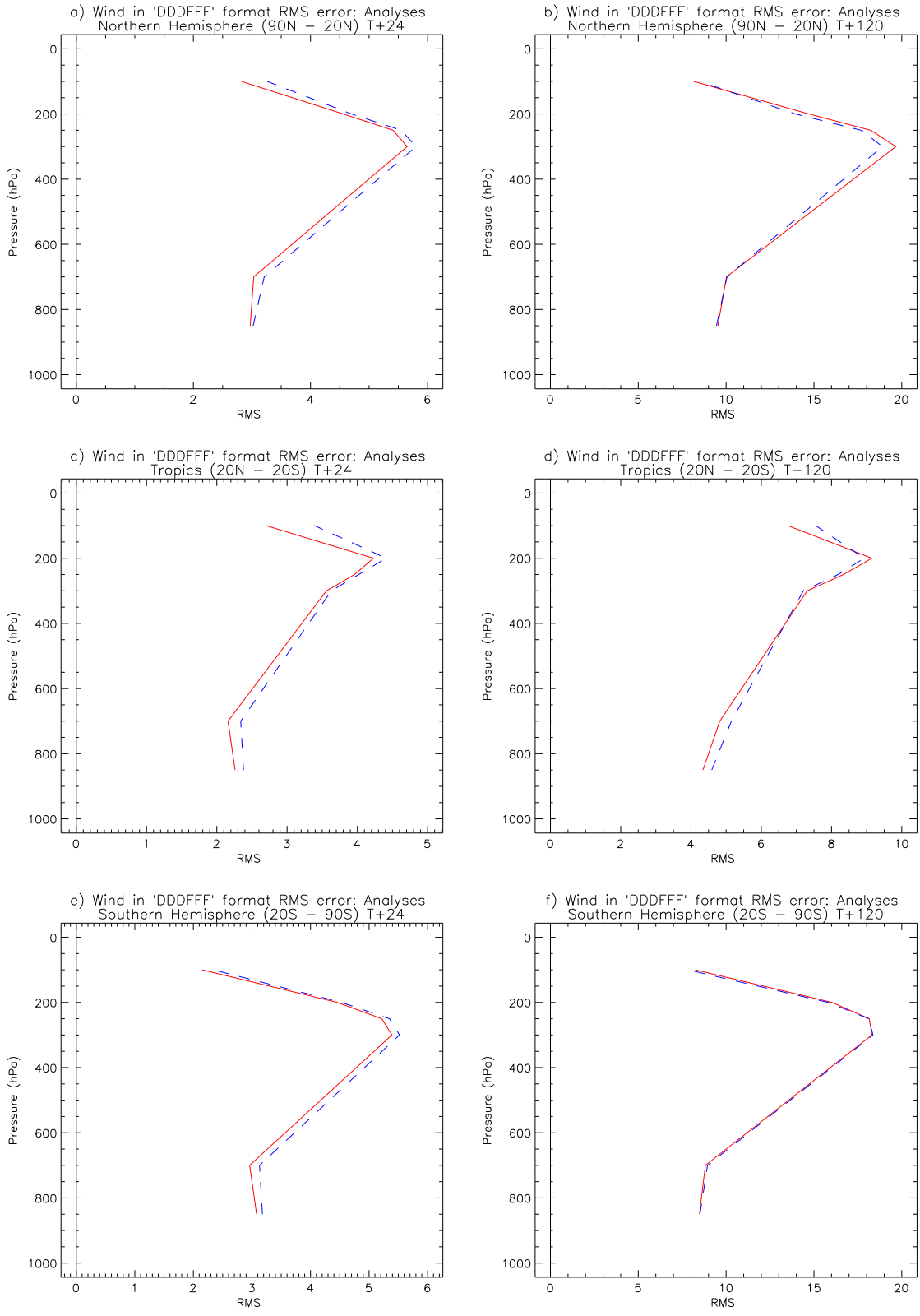

Figure 37: As Figure 32 but for verification against analyses for January 1997.

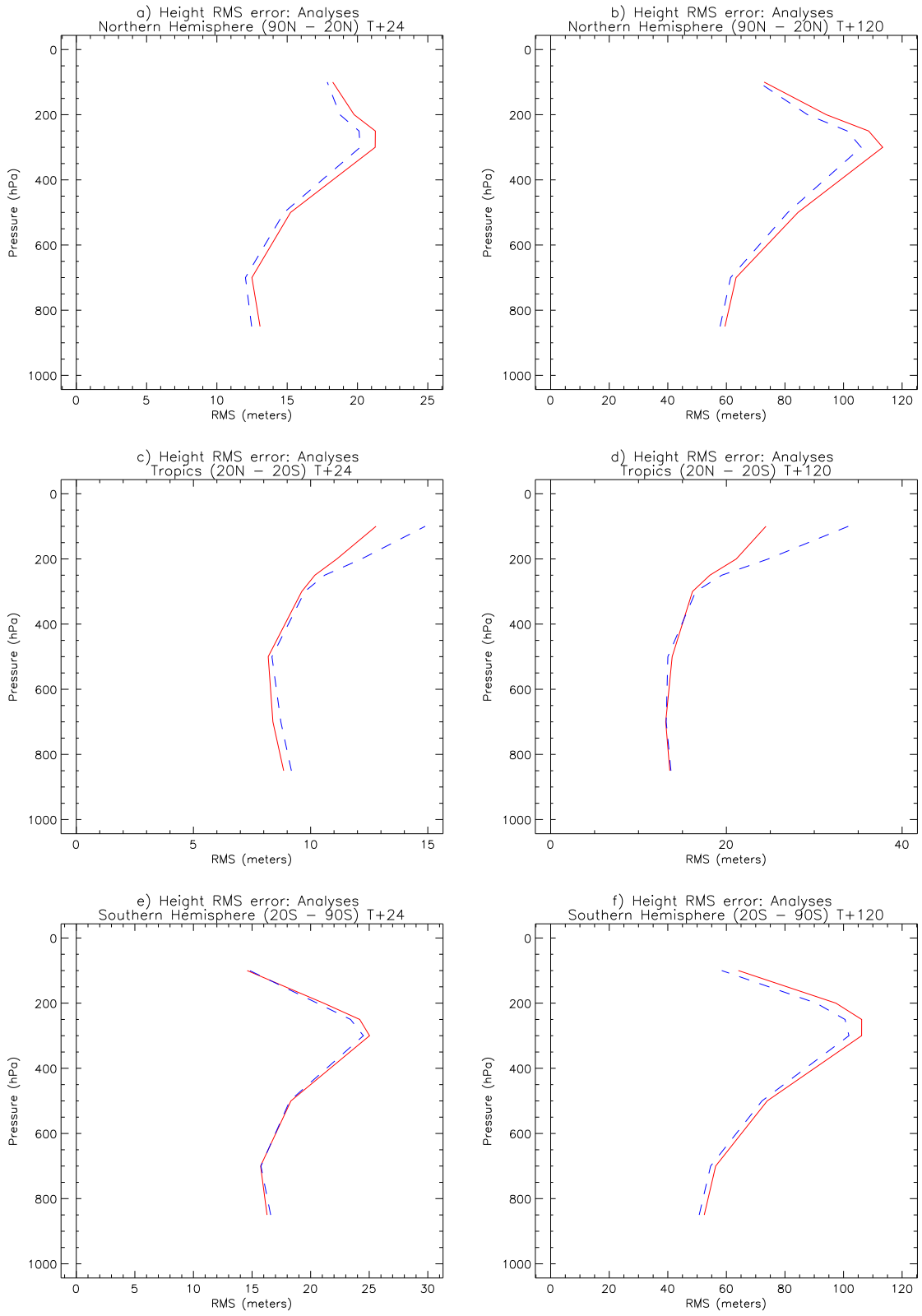

Figure 38: RMS geopotential height errors verified against analyses for January 1997. The solid line is the CONTROL and the dashed line is the high resolution model. (a) NH at T+24. (b) NH at T+120. (c) Tropics at T+24. (d) Tropics at T+120. (e) SH at T+24. (f) SH at T+120.

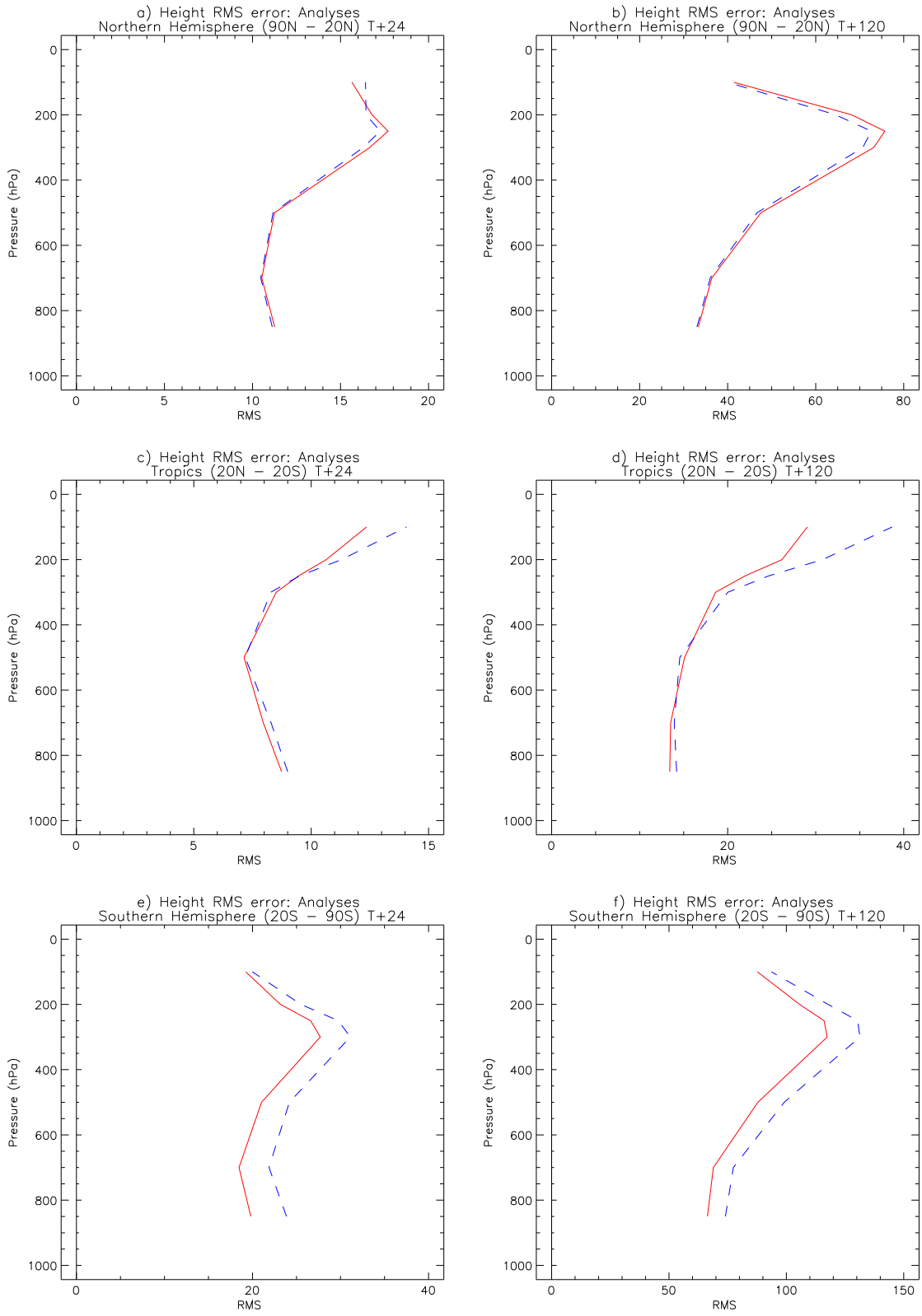

Figure 39: RMS geopotential height errors verified against analyses for July 1997. The solid line is the CONTROL and the dashed line is the high resolution model. (a) NH at T+24. (b) NH at T+120. (c) Tropics at T+24. (d) Tropics at T+120. (e) SH at T+24. (f) SH at T+120.

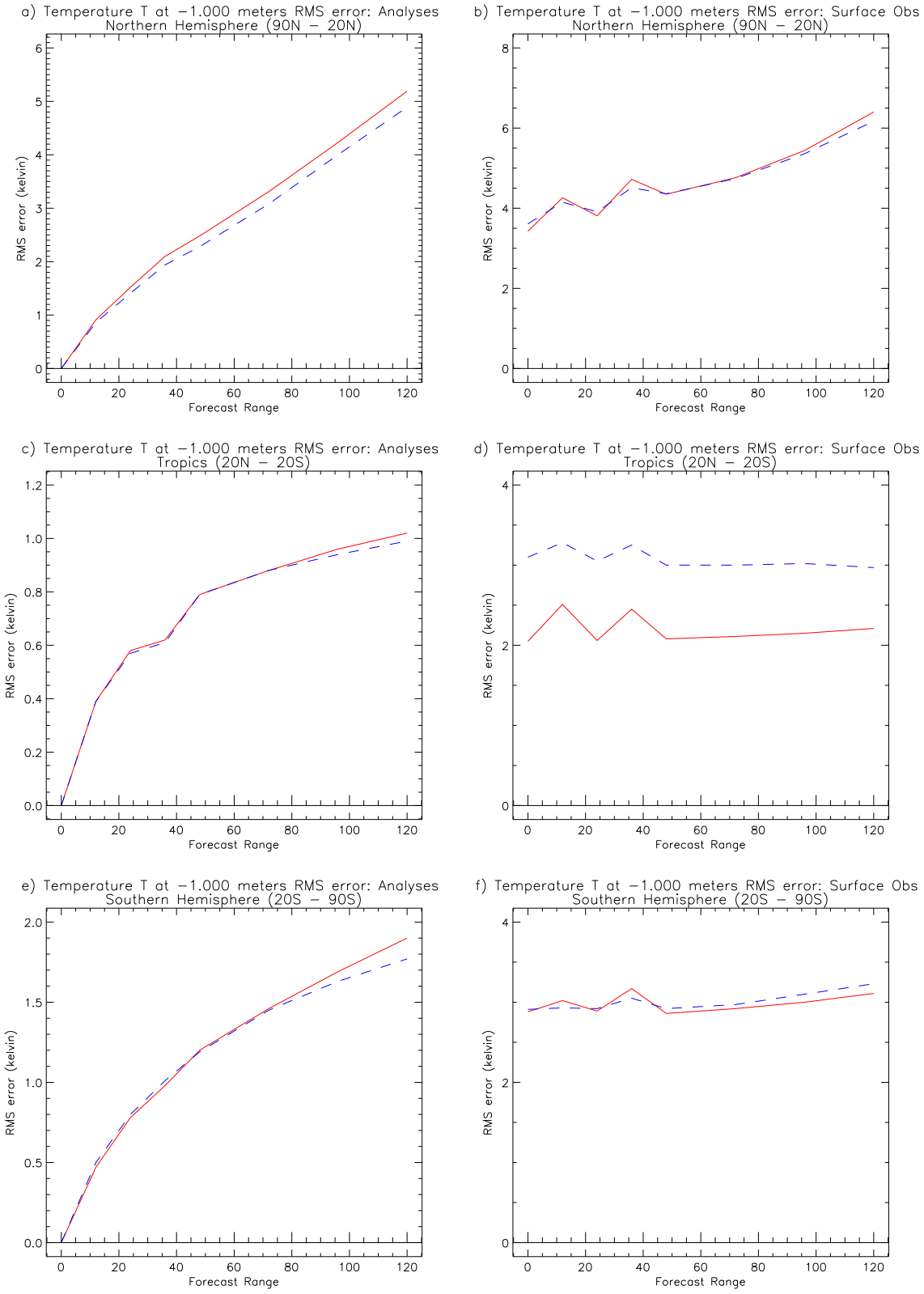

Figure 40: The 1.5m temperature biases RMS errors against analyses and surface observations as a function of forecast range. The solid line is the CONTROL and the dashed line is the HIRES model. (a) Against analyses in NH. (b) Against observations in NH. (c) Against analyses in tropics. (d) Against observations in tropics. (e) Against analyses in SH. (f) Against observations in SH.

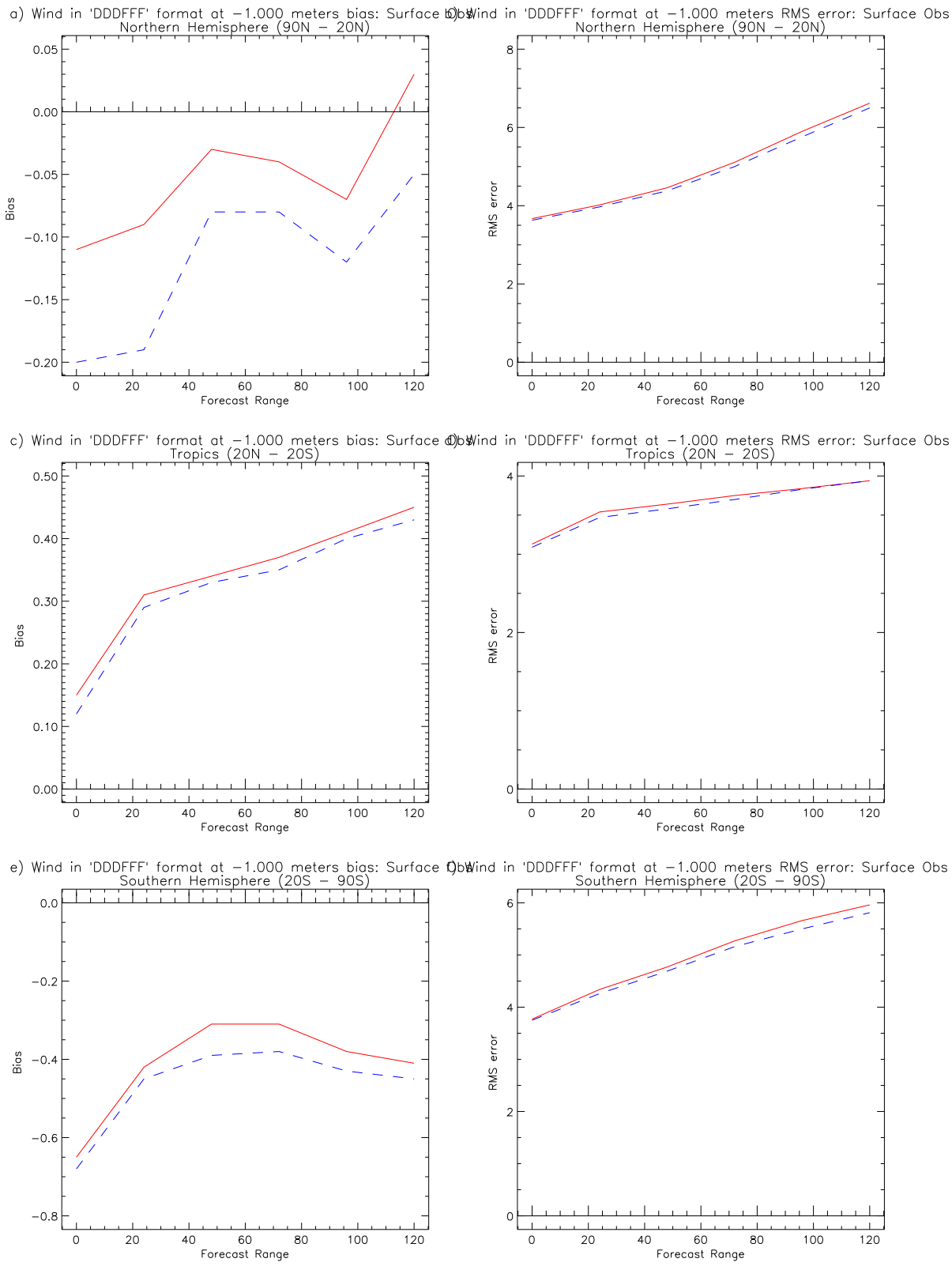

Figure 41: The 10m wind errors verified against surface observations as a function of forecast range. (a) Wind speed bias in NH. (b) RMSVWE in NH. (c) Wind speed bias in tropics. (d) RMSVWE in Tropics. (e) Wind speed bias in SH. (f) RMSVWE in SH.

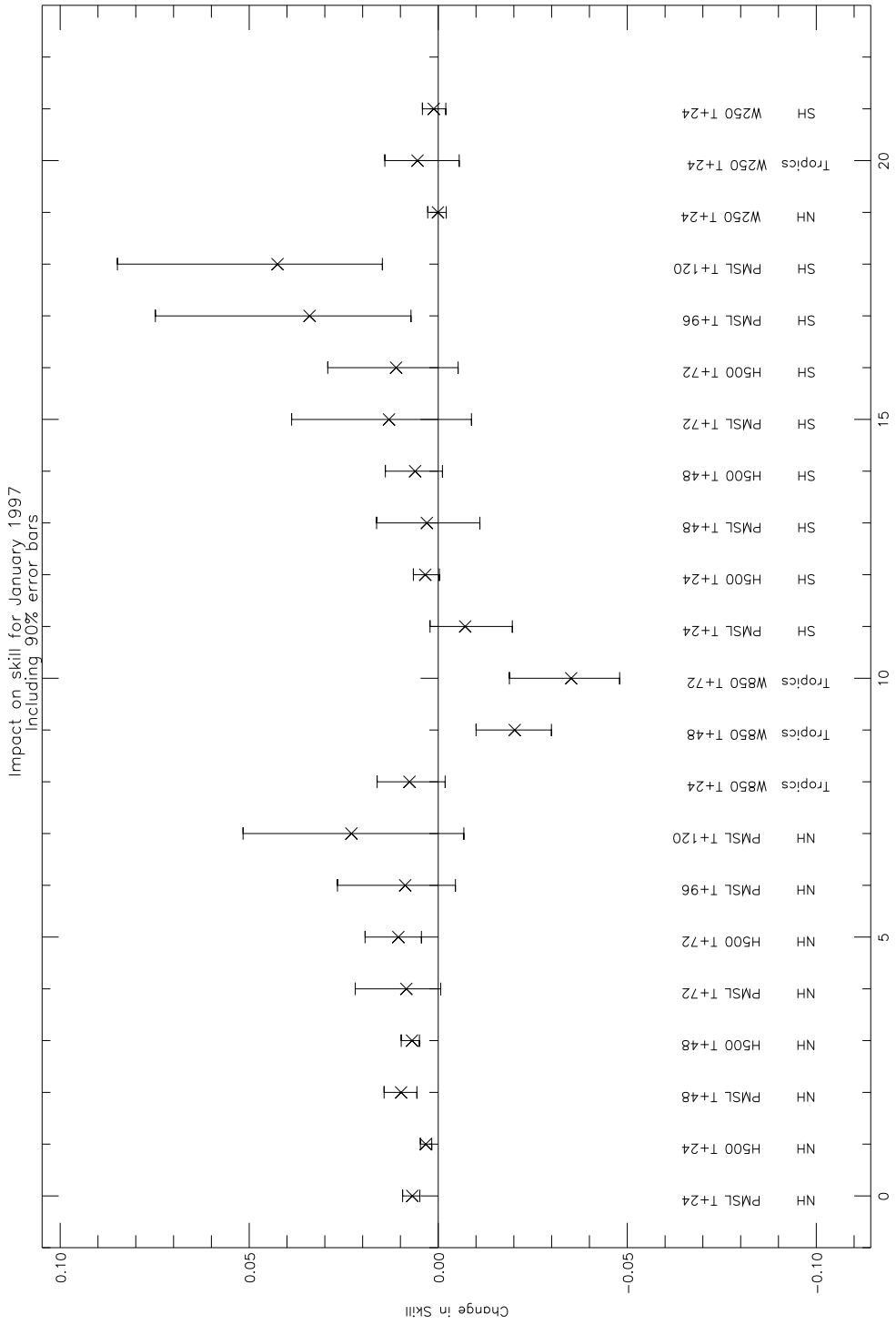

Figure 42: The impact of enhanced resolution on the weighted mean skill for each of the components which make up the NWP index. A positive value implies that the HIRES is more skilful than the CONTROL. See the text for a definition of the weighted mean skill.

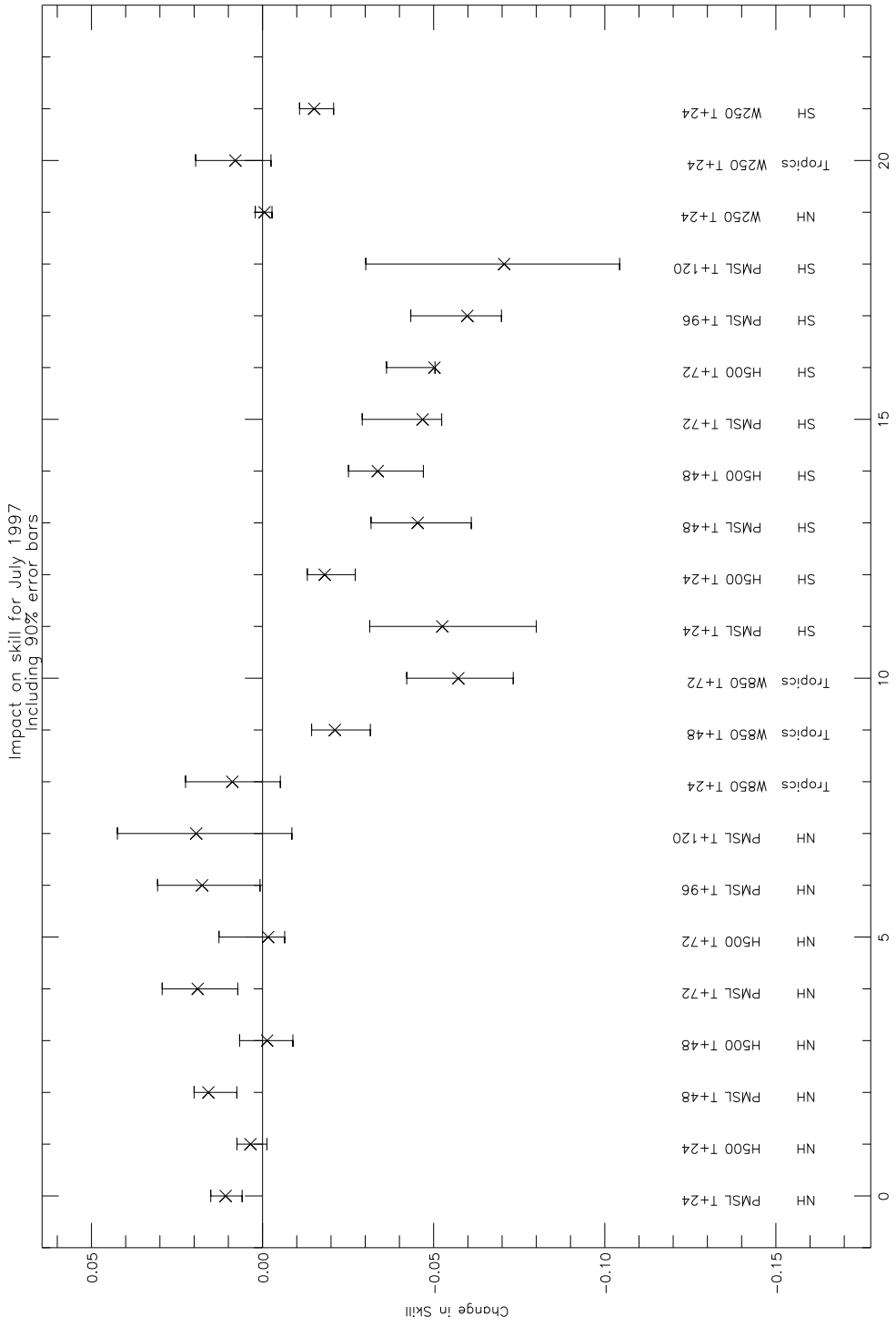

Figure 43: As figure 42 but for July 1997 parallel trial of HIRES.

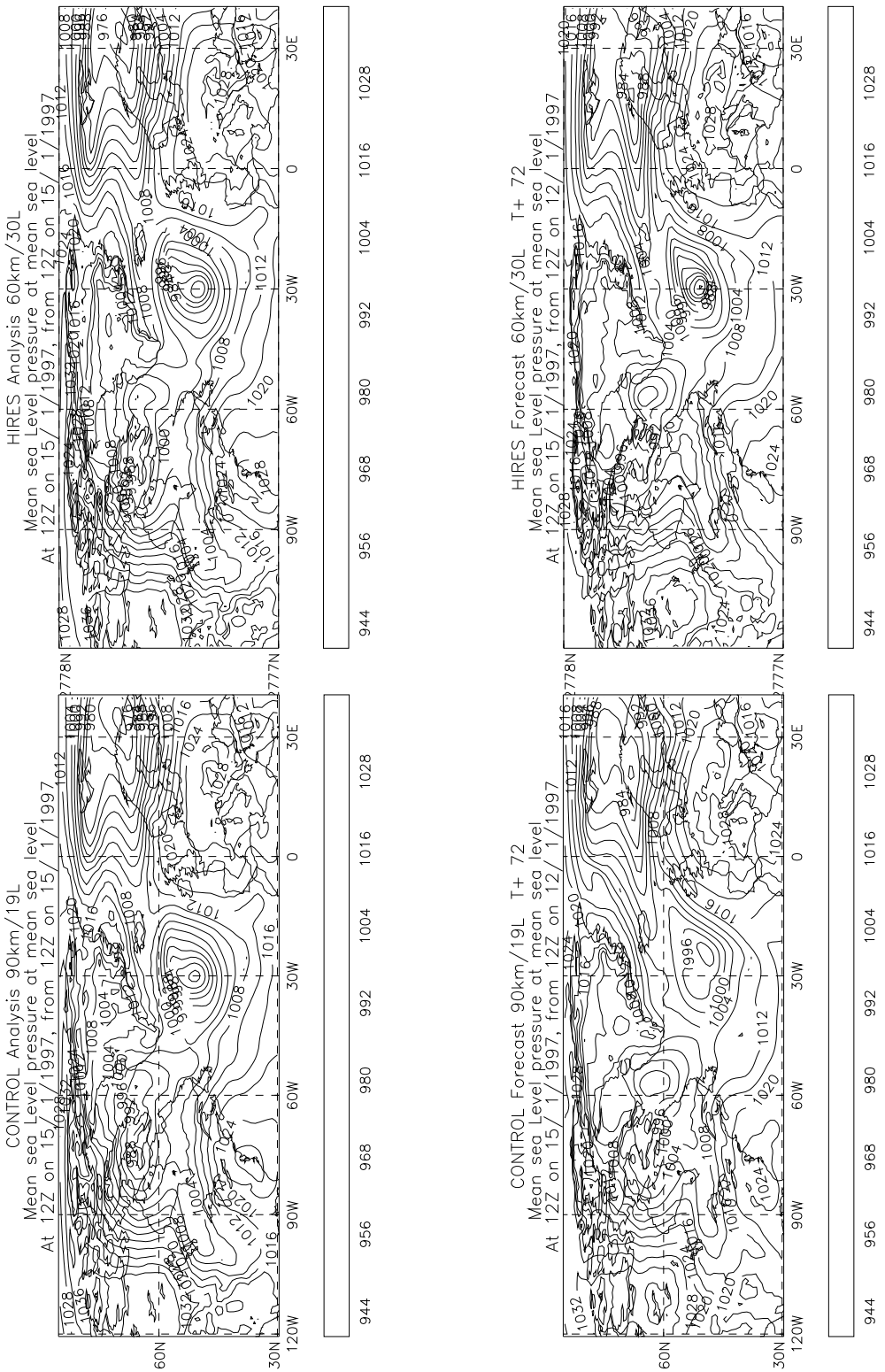

Figure 44: HIRES forecast has low within 8hPa of analysis and a better position than the CONTROL forecast.

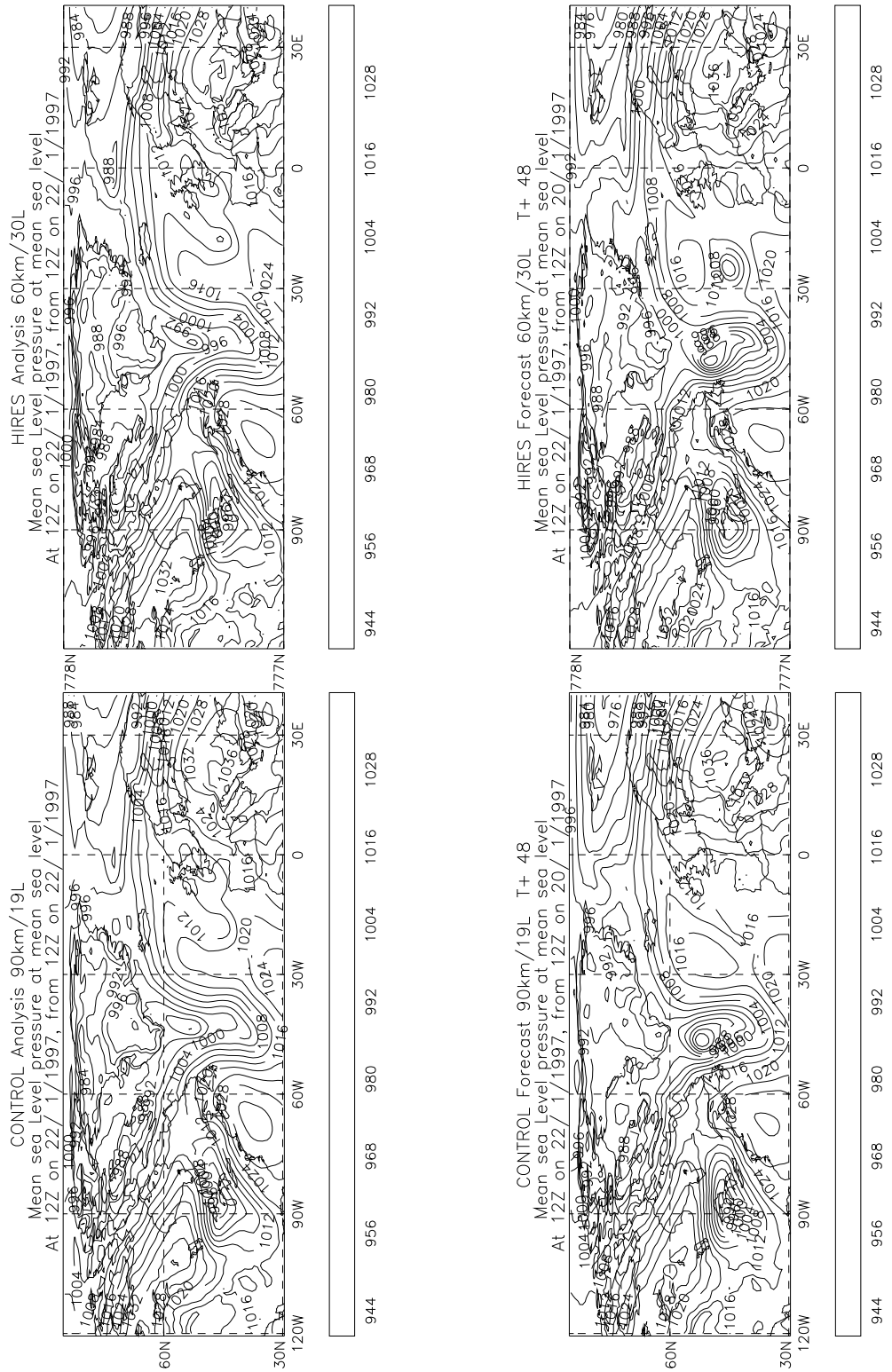

Figure 45: CONTROL forecast correctly has only a trough just west of the U.K. HIRES forecast has spurious ¡1000hPa centre.

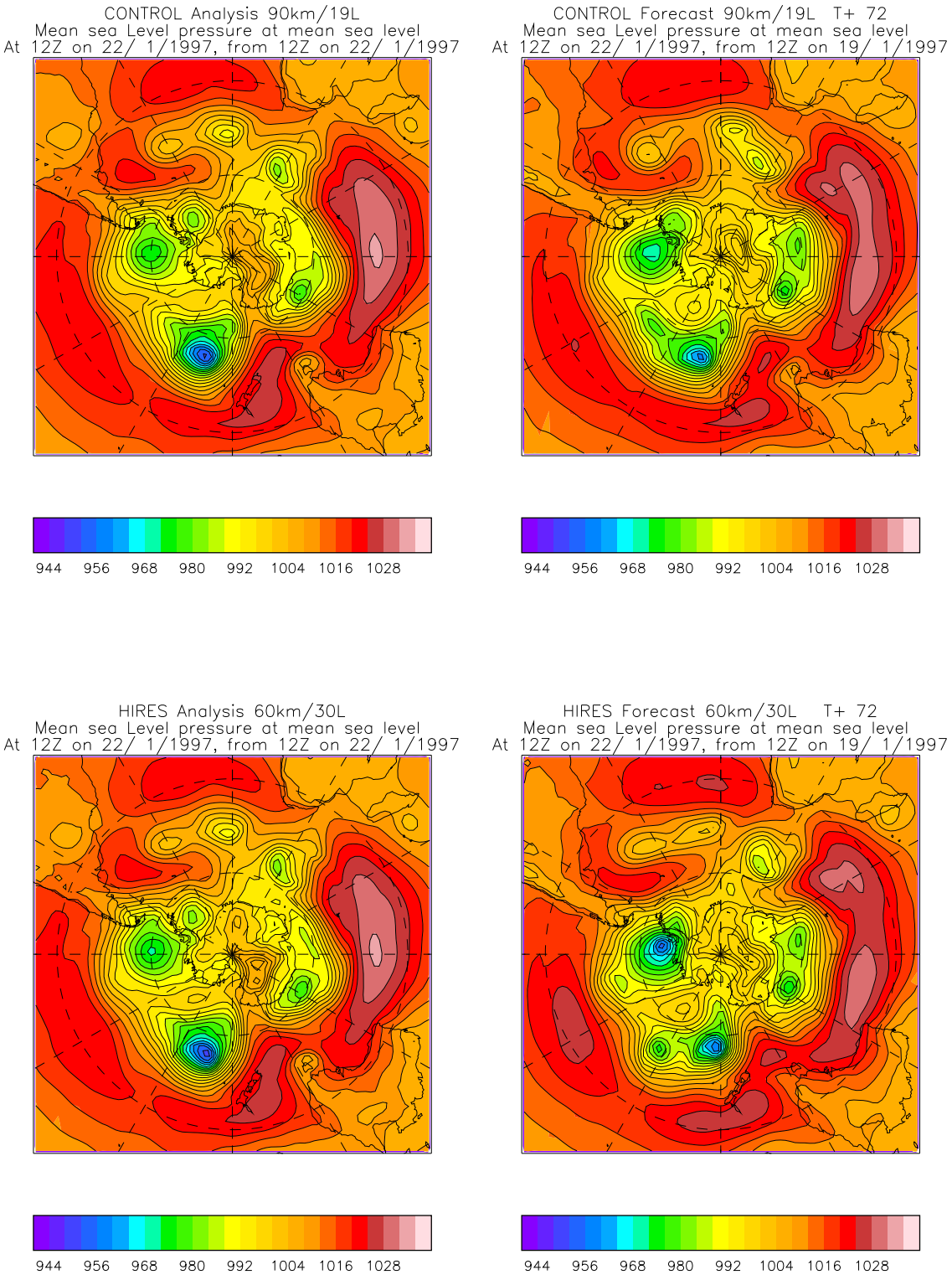

Figure 46: HIRES forecast (bottom right panel) produced 2 low centres further apart than CONTROL (top right).

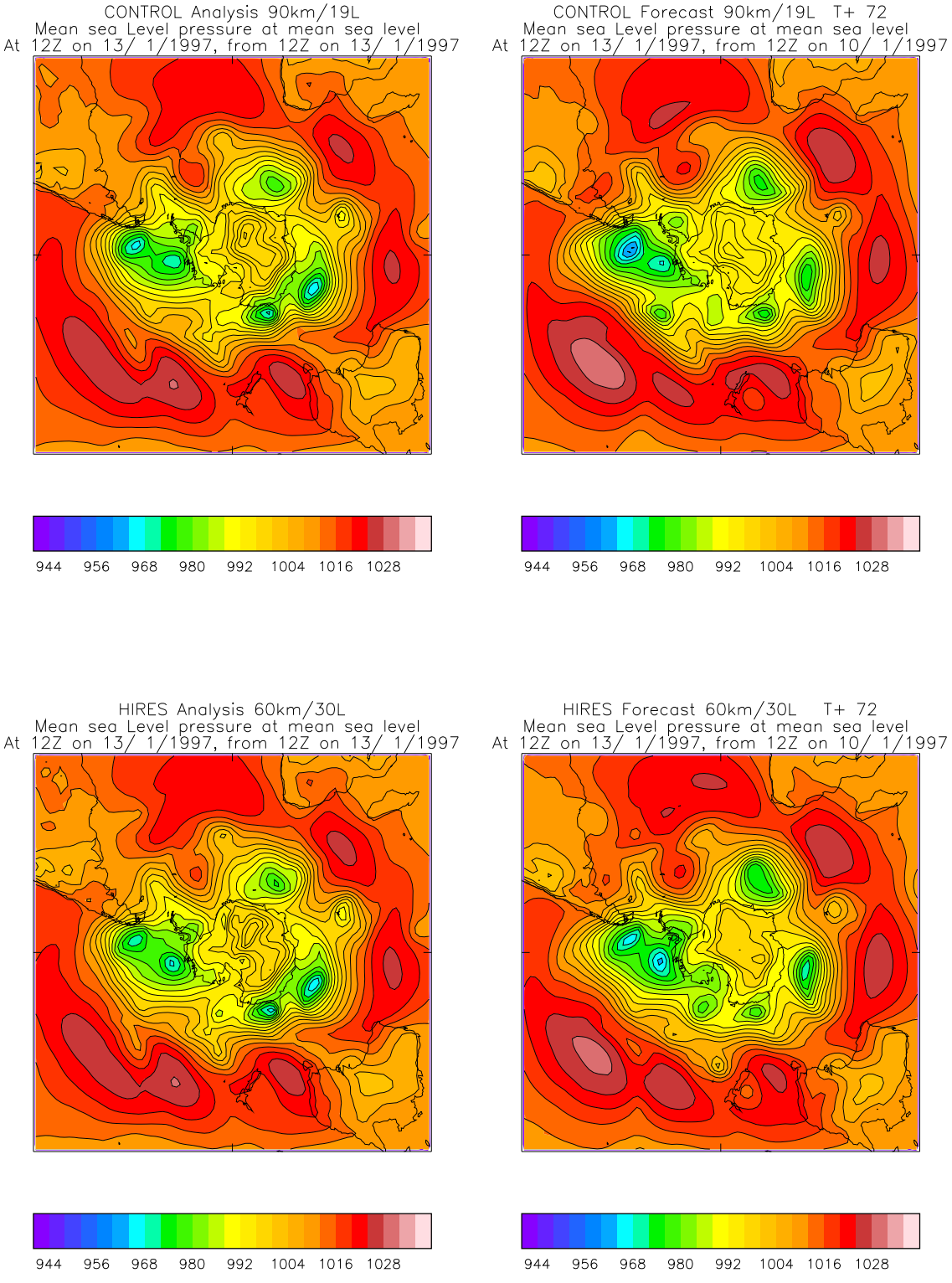

Figure 47: CONTROL (top right) produced a low centre at considerably lower latitude than the HIRES.

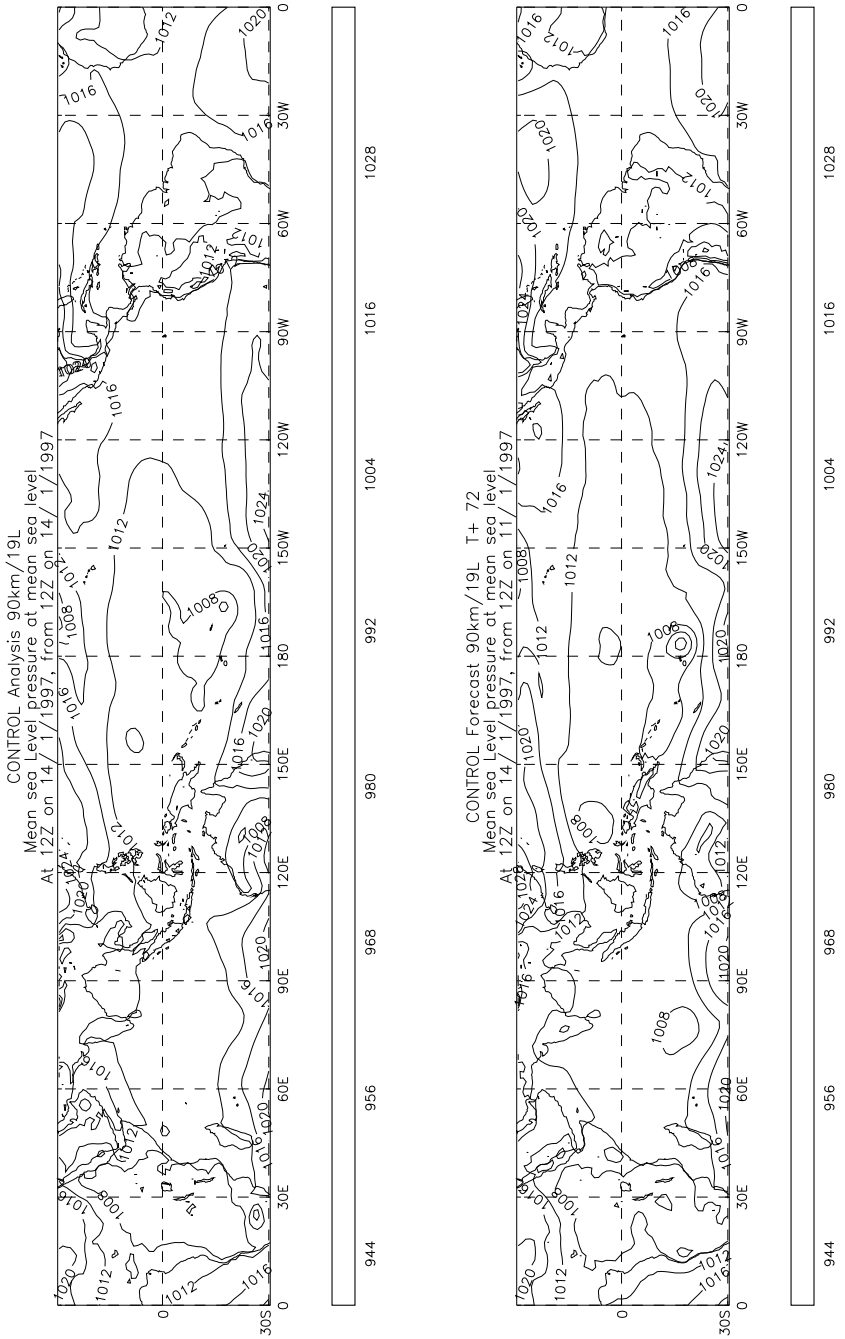

Figure 48: CONTROL analysis and T+72 forecast of tropical cyclone Evan, verifying at 12Z on the 14/1/1997. CONTROL forecast (bottom) has cyclone centre of ¡1000hPa around 15S and 175W. Note shallow centre on analysis.

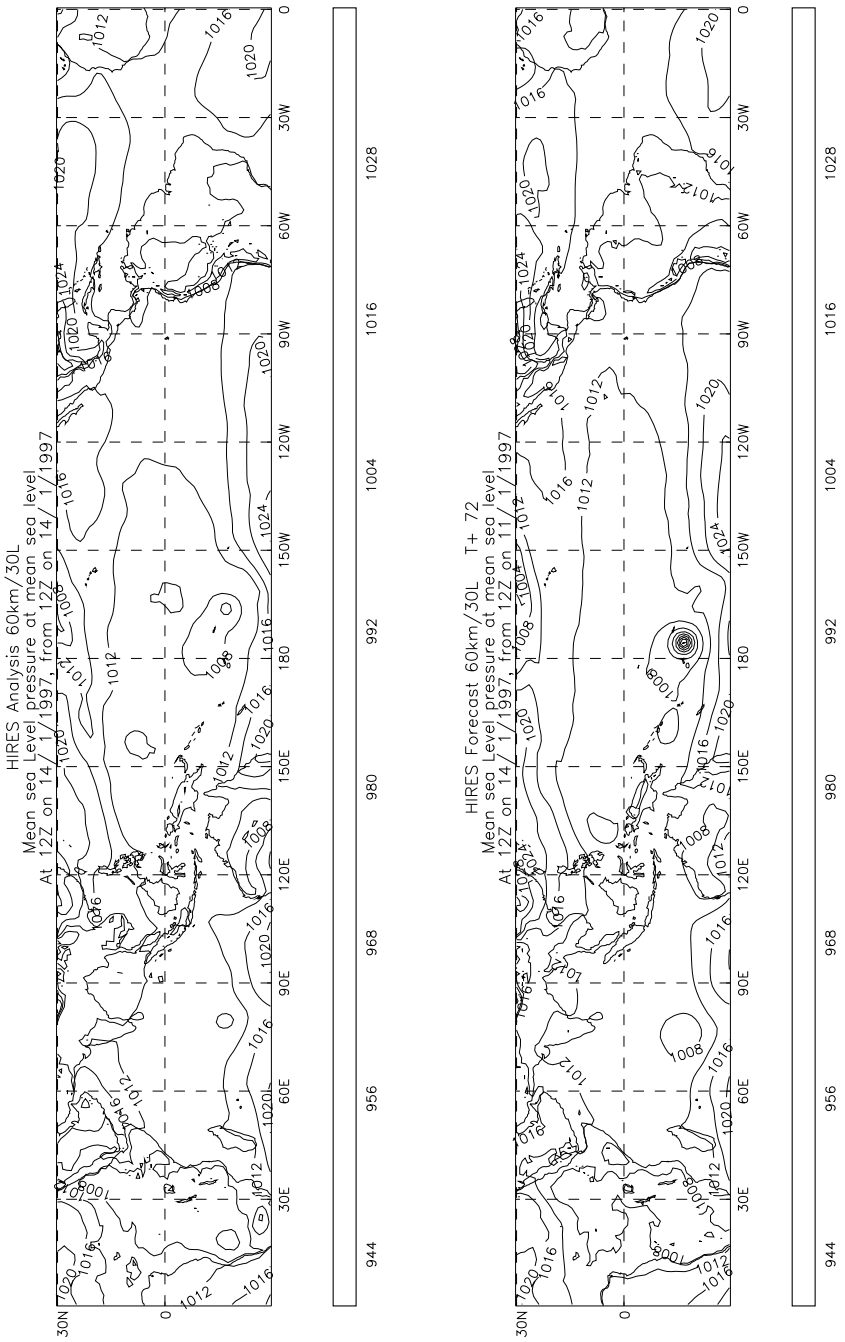

Figure 49: HIRES analysis and T+72 forecast of tropical cyclone Evan, verifying at 12Z on the 14/1/1997. HIRES forecast (bottom) has centre of 980hPa and still with only a shallow centre on HIRES analysis but the local advisory valid 14/0600 UTC gave central pressure as 975hPa.

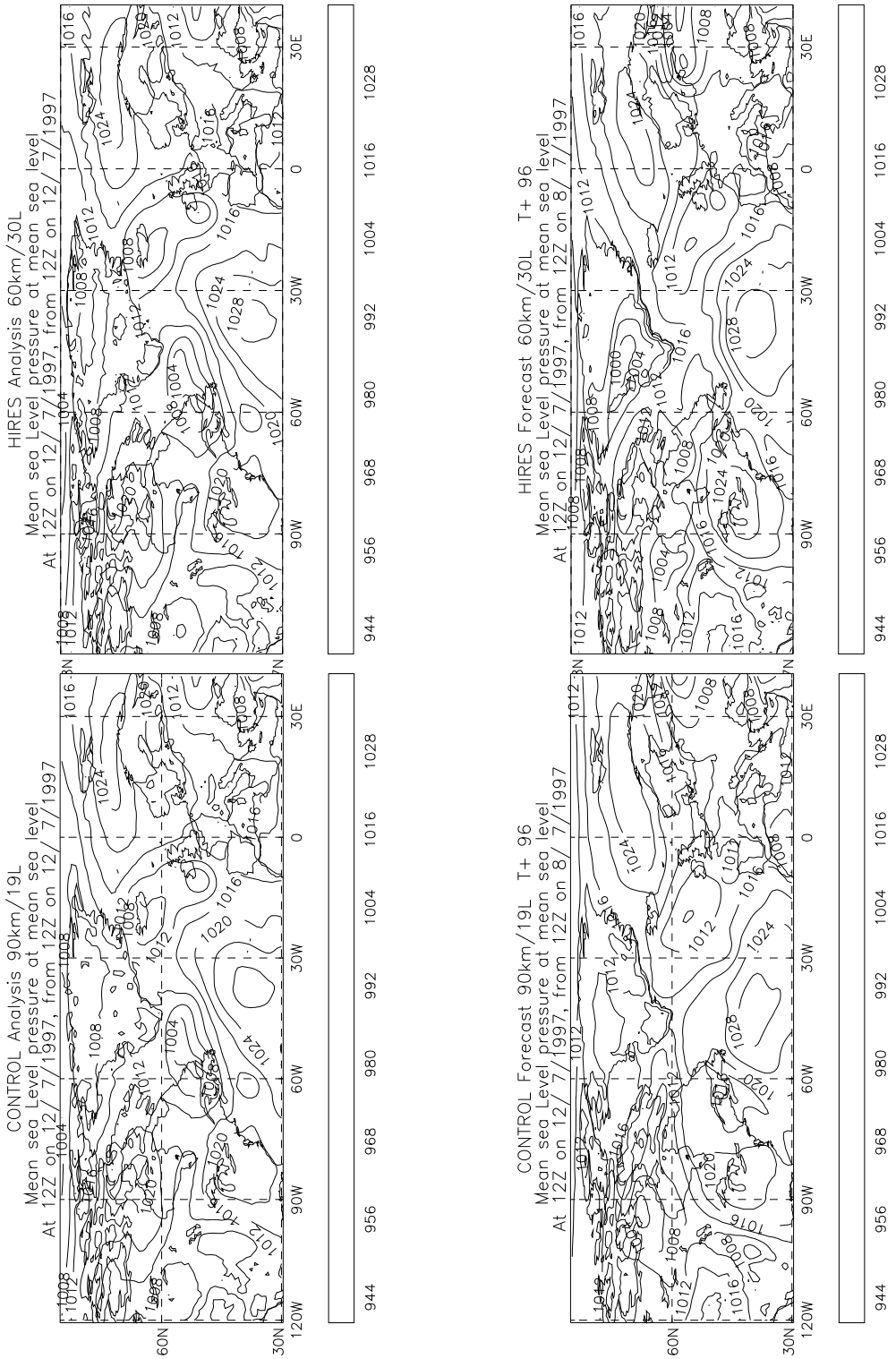

Figure 50: . CONTROL and HIRES analyses and T+96 forecasts of MSLP verifying at 12Z on 12/7/97. HIRES forecast has a better prediction of the shallow depression over Nova Scotia.

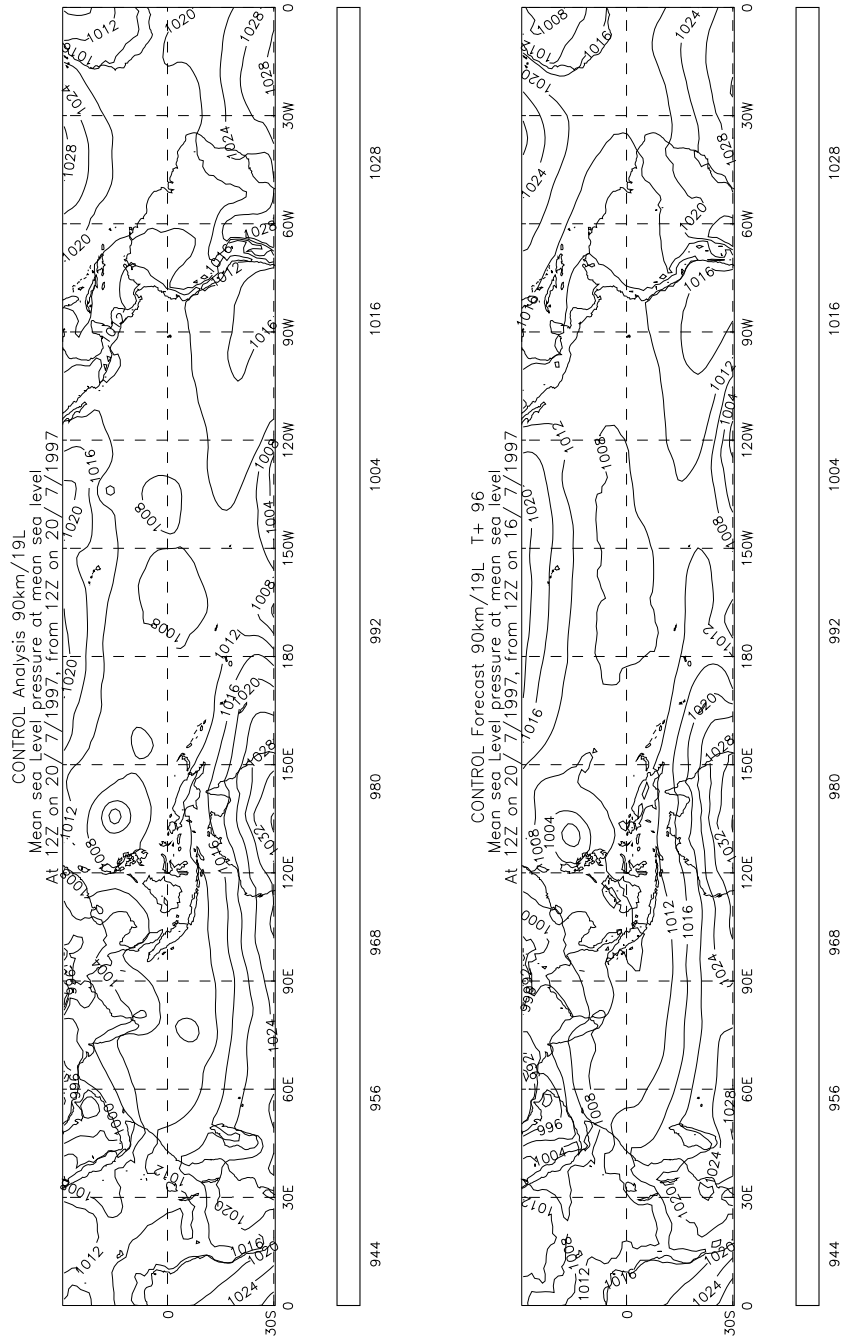

Figure 51: .CONTROL analysis and T+96 forecasts of tropical cyclone Rosie. Verifying at 12Z on 20/7/1997.

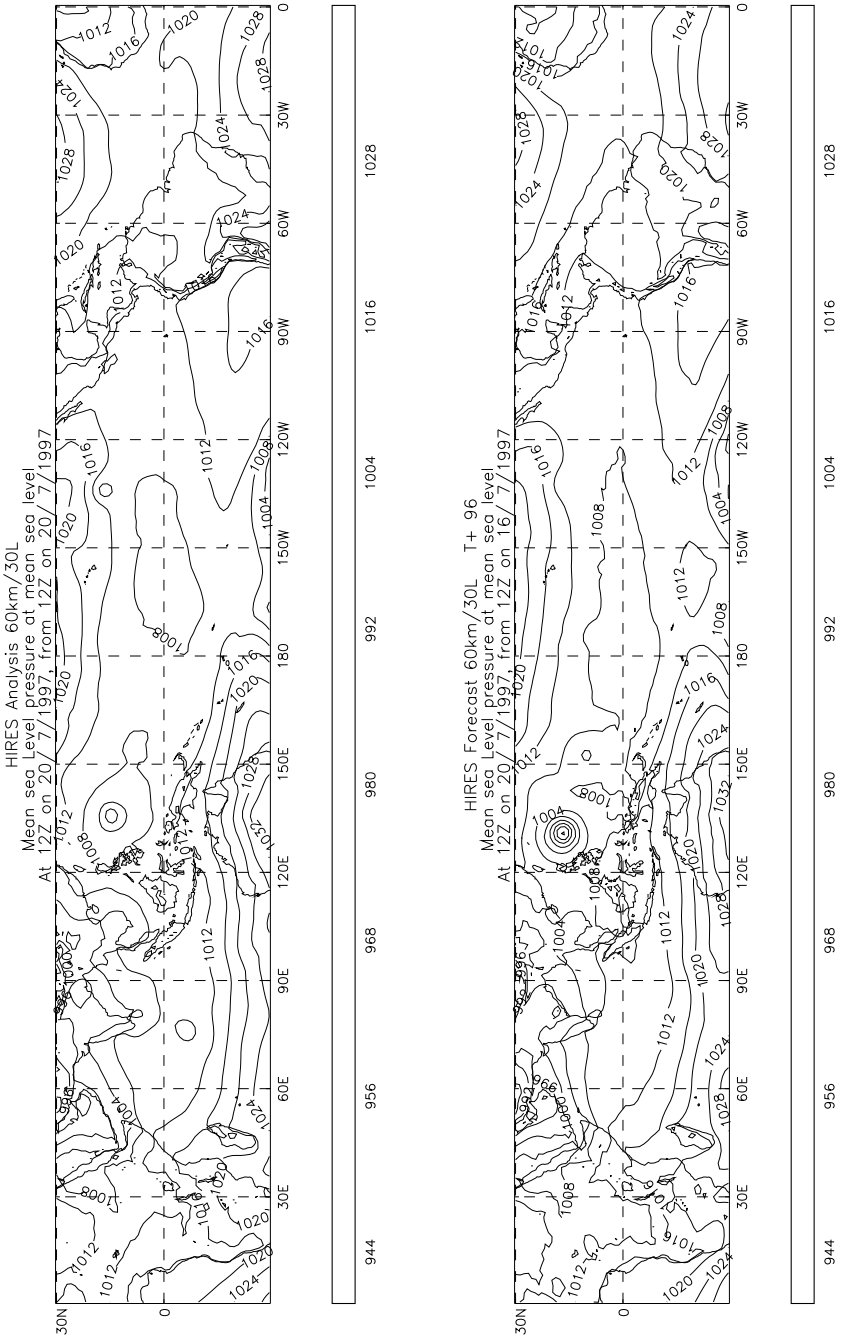

Figure 52: HIRES analysis and T+96 forecasts of tropical cyclone Rosie. Verifying at 12Z on 20/7/1997.